Seed viability versus seed vigour of canola (*Brassica napus* L.) cultivars in South Africa and the impact on establishment

by

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Declaration

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Summary

Laboratory, greenhouse and field trials were conducted in 2020 to compare the effectiveness of general seed quality parameters and certain seed vigour parameters to the actual field establishment success of several common canola (*Brassica napus* L.) cultivars from South Africa. Fourteen different, commonly cultivated, canola cultivars that were available on the South African retail seed market for the year 2020, were obtained from various seed marketing companies. For the sake of confidentiality in this study, the 14 cultivars were randomly assigned a code number from 1 to 14 and referred to by these code numbers. The general seed quality parameters determined in this study included germination percentage, thousand seed mass (TSM) and seed size fractioning. The germination percentages of the cultivars were determined by germinating seed as described by the International Seed Testing Association (ISTA). The TSM of all cultivars was determined by counting out 5 replications of 1000 seed from each cultivar and weighing each replication to determine the mean TSM. Seed size fractioning was done by dividing 3 replicates of each cultivar into three size classes and determining the mean percentage of each size class per cultivar. The size classes were classified as small (<1.7 mm), medium/normal (1.7-2.0 mm) and large (>2.0 mm). The vigour testing parameters used to test seed vigour of all the cultivars included germination and emergence after accelerated ageing (AA), planting depth emergence and drought stress emergence. Accelerated ageing (AA) was done by ageing seed for 0, 24, 48 and 72 hours in a temperature-controlled growth chamber at 42 °C ± 0.5 °C before germination and emergence testing. The planting depth emergence was determined by planting seeds from each cultivar at four different depths, 10 mm, 20 mm, 40 mm and 60 mm. The drought stress emergence was determined by determining emergence of each cultivar while watering was done by an 0.2% Polyethylene glycol 6000 (PEG-6000) solution with an osmotic potential of about -500 kPa, simulating 50% field water capacity. Six canola cultivar field trials were then planted across the production areas of the Western Cape of South Africa to collect field emergence, field establishment, biomass, leaf area index (LAI) and yield data to compare to general seed quality and seed vigour results. The main aim of the study was however to determine the effectiveness of general seed quality and seed vigour to determine potential field establishment. After regression analysis of several general seed quality, seed vigour and field trial results during this study it could be concluded that germination percentage had a moderate predicting ability on field emergence, but seed vigour parameters are best to predict potential field emergence and establishment. Although seed vigour gives a good indication of field establishment, there is no significant correlation with biomass, LAI and eventually yield.

Opsomming

Verskeie laboratorium-, glashuis- en veldproewe is in 2020 gedoen om die verhoudings tussen algemene saadkwaliteitparameters, sekere saadlewenskragtigheidparameters en die werklike veldvestiging sukses van verskeie algemene canola (*Brassica napus* L.) kultivars beskikbaar in Suid-Afrika te ondersoek. Veertien verskillende, algemeen beskikbare, canola-kultivars wat vir die jaar 2020 op die Suid-Afrikaanse saadmark beskikbaar was, is van verskillende saadbemarkingsmaatskappye verkry. Ter wille van vertroulikheid was al 14 kultivars lukraak 'n kodenommer van 1 tot 14 toegeken en in hierdie studie word slegs na hierdie kodenommers verwys. Die algemene saadkwaliteitparameters wat in hierdie studie bepaal is, het ontkiemingspersentasie, duisendkorrelmassa (DKM) en fraksionering van saadgrootte ingesluit. Die ontkiemingspersentasies van die kultivars is bepaal deur saad te ontkiem soos beskryf deur die 'International Seed Testing Association' (ISTA). Die DKM van alle kultivars is bepaal deur 5 herhalings van 1000 sade by elke kultivar uit te tel en dan elke herhaling te weeg om die gemiddelde DKM te bepaal. Saadgrootte-fraksionering is gedoen deur 3 herhalings (± 30 gram) van elke kultivar in drie grootteklasse te verdeel en die gemiddelde persentasies van elke grootte-klas per kultivar te bepaal. Die grootte klasse is geklassifiseer as klein (<1,7 mm), medium / normaal (1,7-2,0 mm) en groot (> 2,0 mm). Die lewenskragtigheidsparameters wat gebruik was om saadlewenskragtigheid van al die kultivars te toets, sluit in ontkieming en opkoms na versnelde veroudering (AA) asook vestigingspersentasies van plantdiepte- en droogtestremmingsproewe. Versnelde veroudering (AA) is gedoen deur saad vir 0, 24, 48 en 72 uur te verouder in 'n temperatuurbeheerde groeikamer teen 'n konstante temperatuur van 42 ° C ± 0,5 ° C, voor ontkieming en opkoms toetse gedoen is. Die vestigingspersentasies van die plantdiepte proef is bepaal deur sade van elke kultivar op vier verskillende dieptes, 10 mm, 20 mm, 40 mm en 60 mm, te plant in 'n potproef. Die vestigingspersentasies van die droogtestremmingsproef is bepaal deur die opkoms van elke kultivar te bepaal, terwyl watertoediening vervang is deur toedienings van 0,2% poliëtileenglikol 6000 (PEG-6000) oplossings met osmotiese potensiaal van ongeveer -500 kPa, wat 50% veldwaterkapasiteit simuleer. Ses canola kultivar veldproewe is daarna op vier verskillende plase regoor die produksiegebiede van die Wes-Kaap van Suid-Afrika geplant om veldopkoms, veldvestiging, biomassa, blaaroppervlakte-indeks (LAI) en opbrengsdata in te samel en te korreleer met die resultate van die algemene saadkwaliteit en saadlewenskragtigheidresultate. Die hoofdoel van die studie was egter om die doeltreffendheid van algemene saadkwaliteit en saadlewenskragtigheid te bepaal om potensiële vestiging in die veld te bepaal. Na regressie-analise van verskeie algemene saadkwaliteit-, saadlewenskragtigheid- en veldproefresultate tydens hierdie studie kon daar tot die gevolgtrekking gekom word dat ontkiemingspersentasie 'n matige voorspellingsvermoë van veldopkoms gehad het, maar saadlewenskragtigheidparameters oor die algemeen die beste is om potensiële veldopkoms en vestiging te voorspel. Alhoewel saadlewenskragtigheid 'n goeie aanduiding gee van veldvestiging, is daar egeter geen beduidende korrelasie met biomassa, LAI en uiteindelik opbrengs nie.

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Preface

This thesis is presented as a compilation of six chapters. Each chapter is introduced separately and is written according to the style of the South African Journal of Plant and Soil to which the intention is to submit Chapters 3, 4 and 5 for publication.

Chapter 1	**General Introduction and aim**
Chapter 2	**Literature review**
Chapter 3	**Establishing general seed quality and emergence potential of available South African canola cultivars**
Chapter 4	**Comparing seed vigour of available South African canola cultivars by exposing them to certain stress related vigour testing**
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Abbreviations

Canola	Canada ('can'), oil ('o') and low acid ('la')
LDL	low-density lipoprotein
CA	Conservation agriculture
TT	Triazine Tolerant
CL	Clearfield
SU's	Sulfonylurea herbicides
Kg	Kilogram
mg	milligram
g	gram
ml	millilitre
mm	millimetre
cm	centimetre
m	metre
ha	hectare
m^2	Square meter
cm^3	Cubic centimetre
g cm^{-3}	Gram per cubic centimetre
LAI	Leaf area index
kg ha^{-1}	Kilogram per hectare
plants m^{-2}	Plants per square meter
plants m^{-1}	Plants per meter
kPa	Kilopascal
°C	Degrees Celsius
%	Percent
N	Nitrogen
P	Phosphor
K	Potassium
S	Sulphate
B	Boron
H_2O	Water
PEG-6000	Polyethylene glycol 6000
TP	Top paper
BP	Between paper
TSM	Thousand Seed Mass
AA	Accelerated Ageing
MGT	Mean germination time

GI	Germination index
MET	Emergence time
EI	Emergence index
FWC	Field water capacity
DAE	Days after first emergence
PM	Physiological maturity
CRD	Completely randomised design
RBD	Randomised block design
ANOVA	Analysis of variance
GLMM	General linear mixed models
LSD	Least significant difference
R	Correlation coefficient
R^2	Coefficient of determination
Apr.	April
Jun.	June
Jul.	July
Aug.	August
Sept.	September
Oct.	October
ISTA	International seed testing association

Chapter 1

General Introduction and aim

1.1 Introduction

Canola (*Brassica napus* L.) is the third largest oilseed commodity produced worldwide, surpassed only by soyabeans and palm oil (Gunstone 2001; Wang et al. 2009). The importance of canola as a crop has increased substantially in the cereal growing areas of the Western Cape to the point that it is now an integral part of several cropping systems and rotations on many of these farms (Mokone 2018). Canola's production hectares in the Western Cape Province of South Africa increased from around 17 000 hectares in the 1999 production season to between 70 000 and 85 000 hectares in 2018 (Sihlobo 2018; GrainSA 2020). The increase in canola production means seed companies are expected to meet the demand of high-quality certified seed to producers to establish their crops. The establishment of any crop is the first most important part of a successful production year, with several factors that can influence the establishment of crops (Finch-Savage and Bassel 2015). Climatic conditions, seed viability and seed vigour are considered some of the most important factors that can influence crop establishment (Finch-Savage and Bassel 2015). When establishing a crop, assuring the uniform and abundant emergence of seedlings to ultimately ensure uniform ripening with minimum seed losses during harvest all contribute to an optimal yield (Hampton and Tekrony 1995; Yang et al. 2014).

The term 'seed quality' describes the potential establishment performance of a seed lot by means of several tested quality aspects (Hampton 2002; ISTA 2020). Seed viability refers to the potential of seed to germinate under suitable conditions and is therefore indicated by germination percentage, which forms part of one of the general seed quality parameters mostly used to describe seed quality (Hampton 2002; Shaban 2013). General quality parameters mostly used to describe seed quality by seed companies in South Africa include germination percentage, seed size and seed mass, in terms of thousand seed mass (SENSAKO 2019; SANSOR 2020).

Laboratory germination results are all obtained under optimal germination conditions and often overestimates the actual field emergence potential of seed lots (Copeland and McDonald 2001). Therefore, the standard germination test may not always be ideal to provide accurate information regarding seed vigour and subsequently expected field establishment performance.

Seed vigour is rather defined as all the properties that determine seed performance in a wide range of environments (ISTA 2020). Therefore, a seed lot with high vigour is seed that is potentially able to perform well even under less-optimal environmental conditions (ISTA 2020). It is believed that to gain information with regards to potential establishment performance of a seed lot, seed vigour can be tested to provide separations between low and high vigour seed lots (Heydecker 1972; Finch-Savage and Bassel 2015).

There is some controversy regarding which seed testing method is best to be used to indicate seed quality by certified seed companies, but most will agree that seed vigour is a better estimation of potential field establishment performance of seed (Hampton and Tekrony 1995). The practice of seed vigour testing as a seed quality indicator has yet to become established in the South African seed industry as in many other parts of the world, especially on canola (Van De Venter and Lock 2013). Certified seed companies generally make use of germination percentage as seed quality and performance indicator which usually fails to take into account the ongoing seed deterioration process, physical seed damage and quality factors which can be reflected by seed vigour testing (McDonald and Copeland 1997; Elias and Copeland 2001).

This study was therefore initiated with the aim to compare the effectiveness of seed viability and seed vigour results, as seed quality indicators, to the actual field establishment success of several certified South African canola cultivars. The aim of the study was investigated by means of three main objectives:

1. The first objective was to determine several general seed quality parameters of South African canola cultivars and compare them to glasshouse emergence results, to determine which parameter best correlates to glasshouse emergence and to try and estimate potential field performance with regards to establishment and ultimately yield.

2. The second objective was to determine separations between South African canola cultivars with regards to seed vigour and compare it to general seed quality results to try and estimate potential field performance with regards to establishment and ultimately yield.

3. The final objective was to gather field trial data from several canola cultivar trials across the Western Cape of South Africa and correlate actual field performance results to general seed quality and seed vigour results.

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Chapter 2

Literature Review

2.1 Canola production

2.1.1 Background

The canola crop is originally of Canadian origin. During World War II several forms of 'mustard oil crops' where available and produced in several countries across the world (Bell 1982). In the late 1950's, Dr Keith Downey and Dr Baldur R. Stefansson began using traditional plant breeding methods to eliminate the undesirable components of rapeseed to try and change the nutritional characteristics of the crop and produce a desired 'double-low' (Low erucic acid and Low glucosinolate) variety (Bell 1982; Canola Council of Canada 2018a). In 1974, the Western Canadian Oilseed Crushers Association finally registered the first 'double-low' variety, Tower®, and classified it as 'canola' (Bell 1982; Canola Council of Canada 2018a). The name 'canola' derived from the words Canada ('can'), oil ('o') and low acid ('la') (Canola Council of Canada 2018b).

Canola is defined as an oil that contains less than 2% erucic acid and less than 30 μmol of 3-butenyl glucosinolate, 4-pentenyl glucosinolate, 2-hydroxy-3- butenyl glucosinolate or 2-hydroxy-4-pentenyl glucosinolate per gram of air-dry solid (Canola Council of Canada 2018b). Canola seed contains a healthy oil which is approved for human consumption by the Heart Foundation since it is low in polyunsaturated fatty acids and has a high percentage of omega-3 fatty acids which leads to a decrease in LDL (low-density lipoprotein) cholesterol levels (Bazinet and Chu 2014; PRF 2018).

In South Africa, canola production increased to such an extent that it now forms an integral part of several cropping systems, especially in the Western Cape, where production hectares increased from around 17 000 ha in the 1999 season to 44 000 ha in 2012, followed by a jump in hectares to the current production area that varies between 70 000 and 85 000, as seen in Figure 1 below (GrainSA 2020). The total production of canola in South Africa is still generally lower than the demand and thus there is scope to increase production even more (Mokone 2018).

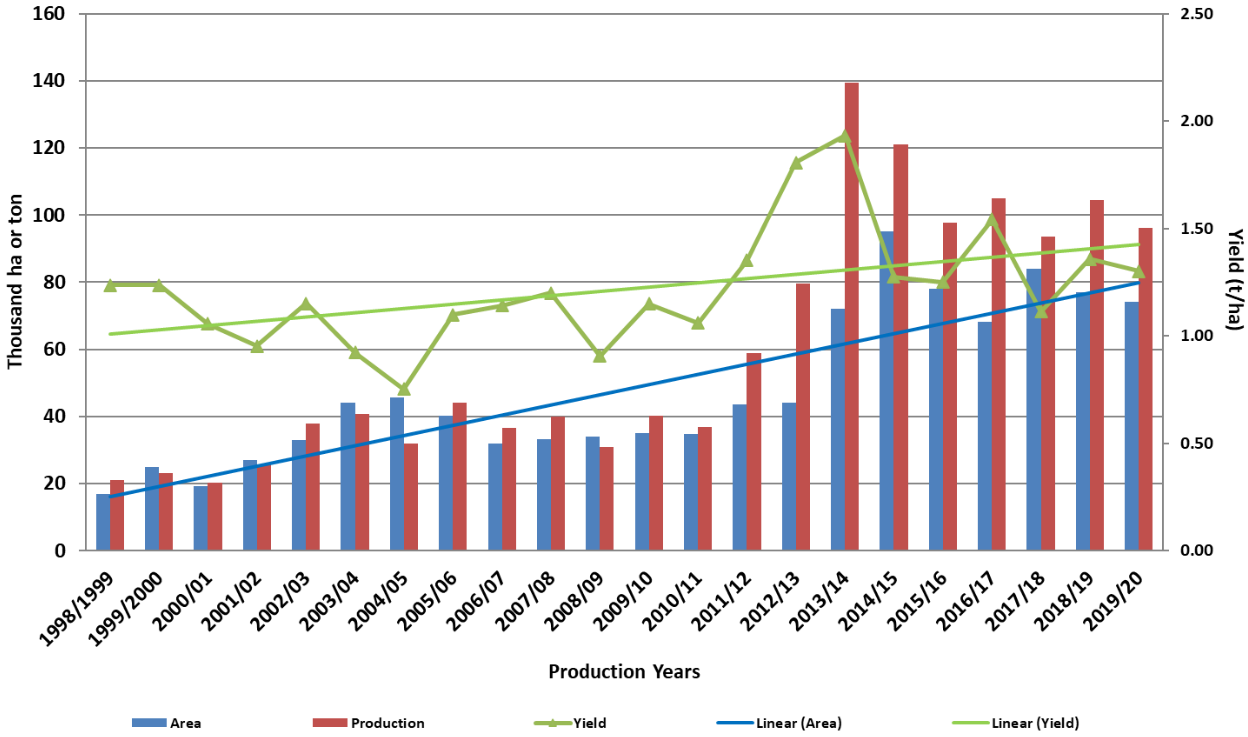

Figure 2.1: South African canola production from 1998 to 2020 (GrainSA 2020).

The increasing production of canola in the Western Cape demands an increase in the supply of certified seed by retail seed companies. With the increasing demand for certified canola seed the competition between seed companies intensifies. Therefore, the seed companies are endeavouring to supply the best quality seed to meet the high demand of producers.

Some doubts have however occasionally been expressed by the farming community about the quality of seed available on the South African retail market. Factors that could negatively influence seed quality may include unbalanced or inadequate nutrition during crop growth, pathogen and insect damage, harvesting or swathing too early, climatic conditions during ripening, physical seed injury during harvest and transport, improper storage and finally overall seed age (Vassilina et al. 2012; Barbos and Moldovan 2014; Yousaf et al. 2016).

2.1.2 Growth

Canola has several different cultivars and varieties branching from the four major species, namely *Brassica napus, Brassica rapa*, *Brassica juncea* and *Brassica carinata* (Kandel and Knodel 2011; PRF 2018). Cultivars within the canola species also range between winter types, intermediary types and spring types which are distinguished by their vernalisation requirement to go from the vegetative state to the reproductive state (Daun 2011; PRF 2018). Cultivars are also classified according to the length of their growth season and their tolerance to certain herbicide groups (GRDC 2015a). Within the Western Cape of South Africa only the spring type *Brassica napus* specie is used for commercial canola production with Conventional, Triazine Tolerant (TT) and Clearfield (CL) cultivars as the available varieties to choose from (de Kock 2018).

Conventional cultivars –	Has no special tolerance towards any herbicide and is optimally planted on weed free fields or where Group A, Group K1 (trifluralin) and Group N (triallate) herbicides can be used to control annual grass weeds and a Group O herbicide (clopyralid) can be used to control certain broadleaf weeds. These herbicides are the most commonly used herbicides on canola and can be used an all varieties. Has a high yield potential (GRDC 2015a; PRF 2018).
Triazine Tolerant (TT) cultivars –	Has tolerance to triazine herbicides, which is a group C1 herbicide used to control annual broadleaf and grass weeds, which can be planted in fields with weed problems in order to rotate herbicides to prevent herbicide resistance. Yield potential is 10-15% lower than that of conventional cultivars (GRDC 2015a; PRF 2018).
Clearfield (CL) cultivars –	Has tolerance towards group A (Fops and Dims) as well as the herbicide Cysure (imazamox), which is a group B herbicide used to control annual broadleaf and grass weeds, which can be planted in fields with weed problems in order to rotate herbicides to prevent herbicide resistance. Clearfield cultivars are also more resistant to Sulfonyl urea herbicides carried over from the previous year’s wheat herbicide applications and give seedlings a major advantage. Yield potential is similar to conventional cultivars (GRDC 2015a; PRF 2018).

The growth stages of a canola plant are difficult to describe since stages partially overlap because of canola's indeterminate mode of growth, unlike winter cereals that show clear growth stages (Norton et al. 2012). Growth stages can roughly be explained by visual plant structures as described by Norton et al. (2012):

1. Seed sown together with required fertiliser (0 days after planting)
2. Germination and emergence (10 - 25 days after planting)
3. Leaf production (25 - 40 days after planting)
4. Stem elongation (40 - 60 days after planting)
5. Bud formation and flower initiation (60 - 75 days after planting)
6. Flowering and anthesis (75 – 115 days after planting)
7. Pod development (115 - 145 days after planting)
8. Seed development and maturation (145 - 180 days after planting)

2.1.3 Establishment of canola

Determining the perfect time of planting canola is always a gamble between getting the seeds into the soil as soon as possible while making sure there is enough moisture for seeds to emerge and grow. Weather conditions therefore play a vital role in determining planting time (Iizumi and Ramankutty 2015). Canola cultivars produced in South Africa all have an indeterminate growth habit and therefore the length of the growth season will be determined by growth conditions (Norton et al. 2012). The indeterminate growth pattern means that the crop development will continue if growth conditions are favourable. The length of the growing season generally also correlates with yields because of this indeterminate growth habit (Norton et al. 2012). Early planting and establishment can therefore induce higher yields if conditions are favourable. Canola also possesses the ability to compensate for early limiting factors and gives more leeway with regards to early planting times (Malhi and Gill 2004). One should keep in mind that planting too early although there is sufficient moisture can also have its own challenges, such as flowering during peak rainy season with increased Sclerotinia problems and crops being ready for harvest before end of rainy season with concomitant harvesting problems. In the Western Cape of South Africa, planting of canola generally takes place between April and May, depending on weather conditions.

Optimal canola planting density for the Western Cape of South Africa is considered to establish 40 to 60 plants per square meter as an average for all varieties, which translates to seeding rates of 2 to 4 kg ha^{-1} (De Villiers and Agenbag 2007; PRF 2018). French and Seymour (2017) however stated that lower planting densities of 1.5 to 3 kg ha^{-1}, translating to 25 to 40 plants per square meter, can also produce good yields given the crop spacing is optimal. Harker et al. (2012) and the Protein Research Foundation (2018) reported that in fact only 50-70% of planted canola seeds will eventually emerge and establish into a productive plant. Therefore, the seeding rates as suggested above already compensates for the seeds that will not emerge in the field. Canola also has the capacity to compensate for low planting densities by forming numerous side branches, which can still lead to a decent yield (Malhi and Gill 2004).

Canola is ideally planted in row widths of 200-250 mm but new studies have shown that wider row spacing performed well enough and is worth consideration (Harries et al. 2015; PRF 2018). In trials conducted in Canada, row spacing of 100 mm, 200 mm and 300 mm were tested and showed that spacing of 200 mm and 300 mm showed higher yields than a 100 mm spacing (Dosdall et al. 1998).

An important practical part of canola establishment is the uniform emergence of seedlings to ensure a uniform stand and ultimately uniform ripening to ensure minimum seed loss during harvest (Yang et al. 2014). Canola should ideally be planted at a depth between 10-30 mm and should be adjusted according to weather predictions (Karow 2014). When canola is planted early and there is not any significant rain predicted in the near future it should be planted at 20-30 mm to prevent the initiation of secondary dormancy with insufficient moisture (Harker et al. 2012; PRF 2018). When planting takes place later in the season where soil moisture is sufficient, planting depth can be reduced to 10-20 mm deep to ensure quick and uniform emergence (Harker et al. 2012).

2.1.4 Fertilisation

Fertilisation of crops is an important factor in any crop production system to ensure optimal yield and quality. Since fertiliser costs are one of the highest input costs in a production system, it is important to only apply the necessary amount for optimal growth, yield and grain quality. First, it is important to know how much nutrients are removed from the soil profile by the canola crop. To get an understanding of the nutritional requirements of canola we can compare the nutrient removal to that of wheat (Table 2.1).

Table 2.1: Average nutrient removal values from the soil profile of canola and wheat crops (FERTASA 2016)

Crop	Nitrogen	Phosphorus	Potassium	Sulphur	Calcium	Magnesium
	kg ha^{-1} nutrient removed per ton of grain produced					
Canola	40	7	9	10	4.1	4
Wheat	21	3	4	1.5	0.33	0.93

In Table 2.1, canola removes, on average, almost more than double the major nutrients from the soil profile, per ton of grain produced when compared to wheat. Since canola only produces approximately 50 – 60% of the amount of grain compared to wheat, the N, P and K requirement of canola is considered the same as wheat. The biggest difference between canola and wheat requirements is the large S requirement of canola. Although these average nutrient removal values give an indication of the fertilisation requirement for canola, it is necessary to do a comprehensive soil analysis, including carbon content and stone fraction, before an accurate fertiliser recommendation for canola can be made (FERTASA 2016).

2.1.4.1 Nitrogen (N)

Besides water, nitrogen is one of the most common limiting factors for optimal canola production (Canola Council of Canada 2019a). Optimal nitrogen fertilisation is critical to obtain the highest yield possible without over fertilising and becoming uneconomical due to unutilized fertiliser. When we look at the N requirements for canola production, we should take into consideration current soil N levels, soil texture, crop rotation, rainfall and the yield objective to make an accurate N requirement prediction (Table 2.2).

Table 2.2: Canola nitrogen (N) fertilisation guidelines (FERTASA 2016)

Area and rainfall	Yield potential	Nitrogen (kg N per ha) for canola after		
		Lucerne*	One-year legume system	Cereal stubble***
SOUTHERN CAPE (65% winter rainfall)				
< 350 mm	1.25 t ha^{-1}	10	25 - 30	30 - 50
350 - 425 mm	1.5 t ha^{-1}	20 - 30	30 - 35	50 - 70
425 - 500 mm	2.0 t ha^{-1}	20 - 30	40 - 45	60 - 90
> 500 mm	2.5 t ha^{-1}	40 - 50	50 - 55	80 - 110
SWARTLAND (83% winter rainfall)				
< 352 mm	1.25 t ha^{-1}		50 - 70**	70 - 90
325 - 425 mm	1.75 t ha^{-1}		70 - 90	90 - 110
> 425 mm	2.50 t ha^{-1}		90 - 110	110 - 130

*Grazing in which grasses are controlled

**Higher value applies to lighter soils

***Includes minimum and no tillage

Since nitrogen fertilisers generally have a high salt index value, particular attention should be given to the distribution of the fertiliser, in order to prevent seed and crop damage (Malhi and Gill 2004). When nitrogen is band placed during planting it is recommended that the amount of N should not exceed 20 kg N ha^{-1} (FERTASA 2016). Generally, two top dressings during the growth season are recommended. The first top dressing should take place approximately 30-40 days after emergence (DAE) and the second at the onset of stem elongation, about 60-70 DAE (FERTASA 2016). On sandy soils, which have a low nutrient holding capacity and where nutrients are easily leached, two equal topdressings are recommended (FERTASA 2016). On heavier soils, with a higher nutrient holding capacity, it is recommended that approximately 65% of the total suggested N topdressing should be applied at 30-40 days after first emergence (FERTASA 2016).

2.1.4.2 Phosphorus (P)

Soil P-values of 36 mg kg^{-1} (citric acid) or 24 mg kg^{-1} (Bray 1) are seen as the norms for soil phosphorus levels for canola production (FERTASA 2016). As a minimum maintenance application, at least 10 kg P ha^{-1} is recommended per year in legume crop rotations (Table 2.3). Applications can be reduced by 30% for production in a cereal rotation system (FERTASA 2016).

Table 2.3: Canola phosphorus (P) fertilisation guidelines for canola in a legume crop rotation system according to soil analysis (FERTASA 2016)

Phosphorus status of the soil *(mg kg $^{-1}$)*		P fertilisation
Citric acid	Bray 1 for pH < 5.5	*(kg P per ha)*
10	6	30
20	14	24
30	20	18
40	28	15
50+	34+	10 (maintenance)

2.1.4.3 Potassium (K)

For heavy-textured, clay soils the norm is considered 80 mg kg^{-1} and for lighter-textured, sandy soils it is considered to be 60 mg kg^{-1} (FERTASA 2016). Grant and Bailey (1993) also suggested that K-additions would only be required if exchangeable K-levels in a soil test are well below 100 mg kg^{-1} (Grant and Bailey 1993). According to these considered norms, additional K fertilisation would not often be required, Table 2.4.

Table 2.4: Canola K-fertilisation guidelines according to soil analysis (ammoniumacetate) (FERTASA 2016)

Heavy-textured soils		Light-textured soils	
Potassium *(mg kg $^{-1}$)*	**K fertilisation** *(kg ha $^{-1}$)*	**Potassium** *(mg kg $^{-1}$)*	**K fertilisation** *(kg ha $^{-1}$)*
< 50	30	< 50	30
50 - 80	20	50 - 80	15
> 80	0 - 20	> 80	0

2.1.4.4 Sulphur (S)

Canola has a much larger sulphur requirement than that of wheat, approximately four times that of barley and wheat. Because of canola's high sulphur requirement, special consideration should be given when the fertilisation program for canola is determined in terms of sulphur since S-deficiency can have a considerable effect on canola seed yield and quality (Malhi et al. 2004). Sulphur requirements should also be done by means of soil analyses and the time of sampling should be done as shortly before planting as possible, since the S content in soils vary during the season. In general, the sulphur requirement of canola is 15-20 kg S ha^{-1} per ton of grain yield (Table 2.5) (FERTASA 2016).

Proper balancing of N and S fertiliser affects seed yield of canola on S deficient soils, therefore S additions are generally done in combination with the N topdressing during the growing season (Malhi et al. 2004). Alternatively, a gypsum (Ca_2SO_4) application of 300 kg ha^{-1} can be made and will be sufficient in most cases (FERTASA 2016).

Table 2.5: Canola sulphur (S) fertilisation guidelines according to soil analysis (FERTASA 2016)

Sulphate (S) *(mg kg $^{-1}$ in soil)*	**Interpretation for fertilisation recommendation**
< 6	Deficient: S application above specific crop requirement (> 15 - 20 kg S ha $^{-1}$)
7 - 12	Sufficient: S application at maintenance level (15 kg S ha $^{-1}$)
> 12	More than sufficient: S application below maintenance level (10 kg S ha $^{-1}$)

2.1.5 Harvest

2.1.5.1 Harvest techniques

Another very important part of any crop production system is the actual harvesting of the crop (Thomas et al. 1991). Harvesting of canola can be conducted by means of two main methods namely direct harvesting or by first swathing and drying canola in windrows and then threshing (Strauss et al. 2012). Both methods have their own advantages and challenges that should be taken into consideration before deciding which method to use.

Swathing first instead of directly harvesting assures more uniform ripening of seed, especially where stands are uneven in nature (Irvine and Lafond 2010). The crop will also dry out faster and in a more uniform manner which at the end will reduce seed loss during harvest, especially in areas prone to strong winds (Strauss et al. 2012).

Directly harvesting of canola also has its own advantages with the main benefit of saving costs on fuel and labour since there are less operations being performed.

Therefore, the biggest disadvantage of making use of the swathing and threshing method is the extra cost involved and for harvesting directly is the risk of seed loss during harvest and during ripening and drying.

2.1.5.2 Time of harvest

Canola generally ripens quickly once it becomes physiologically mature and therefore the optimal harvesting period can be rather short. Canola seed should be below 8% moisture content when harvesting (GRDC 2015b).

Direct harvesting can generally commence as soon as pods start to become yellow, when the pod makes a rustling sound when shaken and most seed have become dark brown to black in colour, with a moisture content below 8% (GRDC 2015b; PRF 2018).

Swathing can generally commence at about 14-28 days after flowering is complete and only about 10% of flowers are still visible. As confirmation pods can be sampled at random across the field, making sure 50% of pods are samples from the middle of the plants and the other 50% split between the bottom and top. Pods can then be opened and if 40 to 60% of seed have turned dark brown to black in colour the canola is ready to be swathed (Strauss et al. 2012; PRF 2018; Canola Council of Canada 2019b). Seed moisture during swathing should be 30-35% (Canola Council of Canada 2019b). Swathing too early can cause severe losses regarding the quality of canola (oil percentage and protein content), thousand seed mass and therefore yield, which will also have a detrimental effect towards seed vigour (Vera et al. 2007). Swathing too late can also cause severe harvest losses (Cavalieri et al. 2016). Threshing can commence as soon as seed moisture drops below 8% which is generally 7-10 days after swathing (PRF 2018; Canola Council of Canada 2019b).

2.2 Seed industry

2.2.1 Seed sampling

When sampling from a seed lot, numerous small quantities of seed should be collected randomly from the main seed lot and then mixed thoroughly to form a composite sample (Desai 2004; ISTA 2020). Several small quantities of seed are then taken at random from different points in the composite sample and then mixed thoroughly to give a submitted sample (Figure 2.2) (Desai 2004; ISTA 2020). The minimum submitted sample for *Brassica napus* (canola) is 100 grams and is generally 10 times more than is required for testing (Desai 2004; ISTA 2020). The process is then repeated until a sample of the correct size for testing is obtained, namely the working sample (Desai 2004). More than one working sample can be generated from the submitted sample (ISTA 2020).

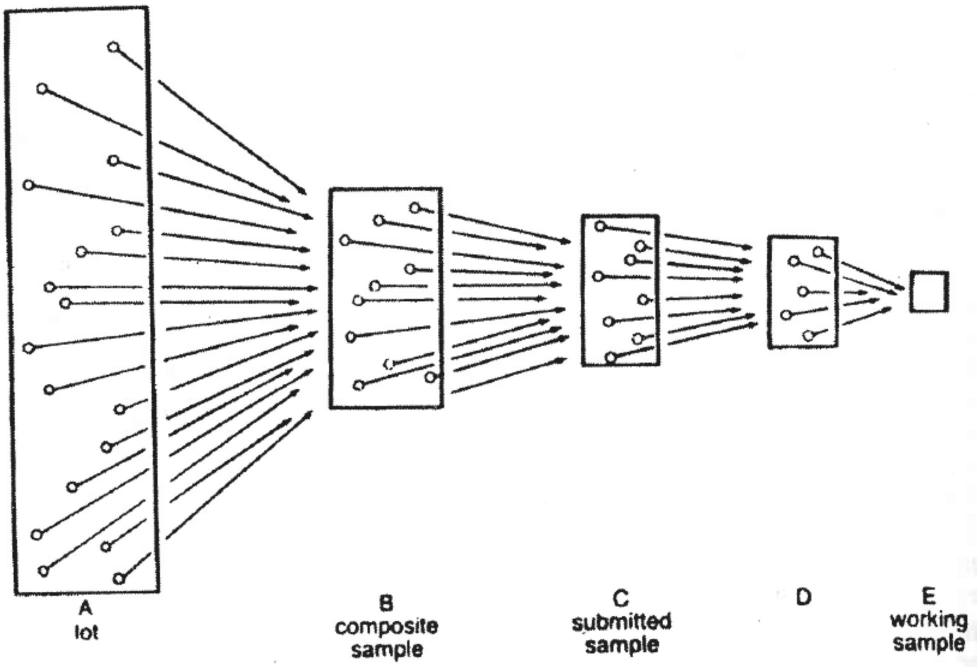

Figure 2.2: Diagrammatic representation of successive stages of sampling from a seed lot (Desai 2004).

Seed treated with insecticide and/or fungicide does not significantly change the shape, size and mass compared to untreated seeds, therefore treated seed are usually tested without removing the seed treatment and according to the same rules as untreated seeds (ISTA 2020).

2.2.2 Seed germination

Seed is seen as the reproductive units of plants, and therefore seed must be able to germinate and establish normal seedlings to develop into a productive plant (McDonald and Copeland 1997). Most seed physiologists believes seed germination to be successful after the radical visibly breaks through the seed coat (Copeland and McDonald 2001; Leeks 2006). The International Seed Testing Association rather defines that, “germination of seed in a laboratory test is the emergence and development of the seedling to a stage where the aspect of its essential structures indicates whether or not it is able to develop into a satisfactory plant under favourable conditions in the soil” (ISTA 2020). Essential structures as indicated by ISTA (2020) include:

i. Root system with an intact primary root

ii. Shoot axis

iii. Visible formation of two cotyledons (dicotyledon)

For canola germination either the top paper (TP) or the between paper (BP) method can be used to determine the mean germination percentage (ISTA 2020). The top paper method is where seeds are placed on top of a double layer of moist absorbent paper and for the between paper method seeds get placed between the two absorbent layers of paper. The TP method is preferred to ensure easier counting of germinated seeds (ISTA 2020). Four replicates of 100 seeds should randomly be sampled from the submitted sample of a seed lot (ISTA 2020). The 100 seeds must be placed onto a double layer of moist Whatman filter paper inside a sterile petri-dish with a fitting lid. The samples should then be positioned into a temperature-controlled growth chamber at 20°C for 16 hours and 30°C for 8 hours. Germination should then be assessed at 5 days and 7 days only for normal seedlings as described by Desai (2004) and ISTA (2020).

In South Africa the minimum certification germination for canola as stated in the plant improvement act of 1976 (ACT No. 53 OF 1976) is 70% (Didiza 2002). Hampton and Coolbear (1990), however stated that a low germination test percentage, i.e. below a norm of 90%, suggests that under optimal conditions the seed quality of a certain seed lot is questionable and physiological seed deterioration has begun.

Laboratory germination results are obtained under optimal germination conditions and regularly overestimates the actual field emergence potential of seed lots (Copeland and McDonald 2001). This indicates that the standard germination test may not be ideal to provide accurate information regarding field establishment performance and seed vigour.

2.2.3 Seed emergence

Good crop establishment and seed emergence is one of the most challenging factors when it comes to crop production in commercial or research settings (Chivas et al. 1998). Crop seeding and establishment efforts are typically poorer in arid to semi-arid conditions (Lysne and Pellant 2004). Seed emergence and crop establishment is the first most important factor in crop production systems and has a determining effect on the total yield, therefore seed needs to emerge as uniformly and abundantly as possible (Finch-Savage and Bassel 2015).

2.2.4 Seed vigour and seed vigour testing

Chronological age, certification class and germination values of seed lots are often the same, but differ significantly in overall field performance and germination after storage (Hampton 1999). These performance differences are potentially a result of varying seed vigour of lots. Germination tests fail to take into account the ongoing seed deterioration process, physical seed damage and quality factors which can be reflected by seed vigour testing (Elias and Copeland 2001).

ISTA (2020) defines seed vigour as, “the sum of those properties that determine the activity and performance of seed lots of acceptable germination in a wide range of environments”. Therefore, a seed lot with high seed vigour is seed that is potentially able to perform well even under sub-optimal environmental conditions (ISTA 2020). It is believed that information relating to the potential field performance of a seed lot can be represented by seed vigour. Seed vigour can therefore be used to provide separations between low and high vigour seed lots.

The practice of regular seed vigour testing as a seed quality indicator has yet to become established in the South African seed industry as in many other parts of the world, especially on canola (Van De Venter and Lock 2013). Therefore, no comparison between canola cultivars can be made regarding expected field performance potential and seed vigour.

Seed vigour testing is a set of tests done on a seed lot to gain information regarding the performance potential and quality of the seed in a range of environmental and climatic conditions, as well as the storage potential of seed lots (ISTA 2020). Seed vigour testing can be done to establish distinct separations between high and low vigour canola seed lots. According to Hampton (1993) a vigour test should be able to provide a more sensitive index of seed quality compared to the standard germination test, and to consistently rank seed lots in terms of potential establishment performance in the field. There are a couple of different ways to determine seed vigour. The following are a couple of commonly used vigour testing techniques.

2.2.4.1 Seed mass and seed size

Seed mass and seed size are both quality parameters of canola seed. It is believed that the higher the quality, the higher the vigour of the seed will be (Elliott and Rakow 1999; Elliott et al. 2007a). Thousand seed mass (TSM) and seed size are also considered to be an indication of seed vigour and correlate with seed plumpness. The theory is that the bigger the seed, the higher the TSM and the better the vigour of the seed lot will be (Heather and Sieczka 1991). The TSM for *Brassica napus* (canola) generally ranges between 3 grams and 7 grams with the average between 4 grams and 5 grams (Elliott et al. 2007a). Normal sized seed for canola is considered to be in the range of 1.7-2.0 mm and seeds smaller than 1.7 mm in diameter are considered small and will most probably have a low seed vigour (Elliott et al. 2007a).

In conclusion the literature shows that seed mass and seed size is predictive of the seed vigour and establishment under field conditions (Snider et al. 2014).

2.2.4.2 Accelerated Ageing (AA)

Vigour testing provides valuable results regarding the estimation of physiological age, condition and quality of a seed lot (Elias and Copeland 1997). Accelerated Ageing is considered one of the most popular seed vigour testing methods worldwide (Fessehazion et al. 2008).

The AA test is designed to expose seeds to aggressive ageing conditions, through humidity and heat, in a climate-controlled chamber to induce seed deterioration. Seed lots with high vigour should be able to withstand these accelerating conditions as they deteriorate at a slower rate than seed lots with low vigour (Hampton and Tekrony 1995). After seed ageing, seeds are evaluated to determine the new germination percentage. Pre-ageing and post-ageing germination tests that provide similar results indicate higher seed vigour of a specific seed lot (Elliott et al. 2007b). The results of the AA test has also been successfully correlated to emergence and establishment in several plant species, including canola (Hampton and Tekrony 1995; ISTA 2020).

The accelerated ageing (AA) procedure for canola is conducted by ageing seeds from a seed lot at 42°C for 0, 24, 48, and 72 hours using the wire-mesh tray method as described by Hampton and Tekrony (1995), Elias and Copeland (2001) and ISTA (2020). The procedure makes use of an AA box, consisting of an outer plastic box with a tight-fitting lid into which a plastic wire-mesh tray is placed (Figure 2.3). One single layer of seed from each lot is spread evenly onto the wire mesh and positioned into the plastic AA box before placing in a temperature-controlled environment. There is a small amount of water underneath the wire mesh tray inside the plastic AA box to create an environment with a 95 - 100% relative humidity (RH) (Elias and Copeland 1997). The water underneath the wire mesh tray should not come in contact with the mesh or the seeds to prevent germination from taking place (Elias and Copeland 1997).

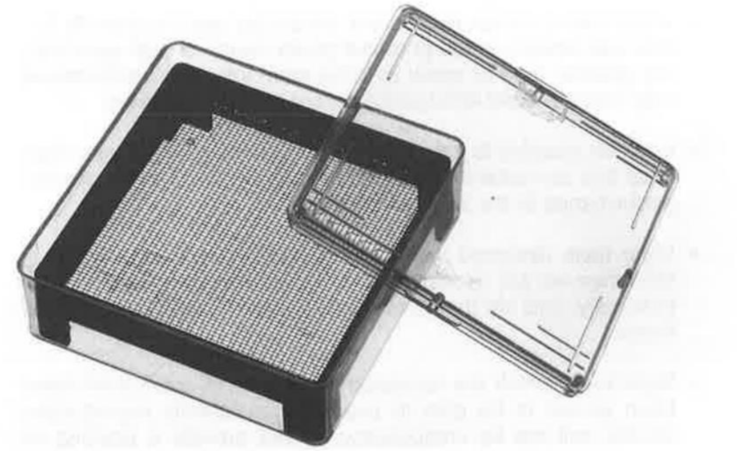

Figure 2.3: Plastic box with wire mesh screen frame to hold seed for ageing (AA box for wire mesh method of ageing seed) (Tekrony 1993).

2.2.4.3 Planting depth

Seed emergence and crop establishment is one of the most important factors in crop production systems and has a determining effect on the total yield, therefore seeds need to emerge as uniformly and abundant as possible (Finch-Savage and Bassel 2015). Planting depth plays a major role in the uniform and successful emergence of seeded crops, considering the energy needed by the seed to emerge above the soil surface (Finch-Savage and Bassel 2015). Seeds with higher vigour will emerge better even from deeper planting depths, therefore planting depth can be used as a vigour test (Larsen 1964; de Oliveira et al. 2019). Differences in seed vigour can be established by assessing emergence results of seeds planted at different depths, especially at deeper than normal planting depths which will serve as a stress factor for seeds. The speed of emergence from different depths can also give good indication of the seed vigour of a seed lot.

2.2.4.4 Drought resistance

The production of annual crops has grown ever more difficult with climatic changes presenting more and more challenges for crops (Challinor et al. 2014). One of the most challenging factors in the production of crops is the irregular nature of rainfall events and therefore crops needs to be adapted to be drought tolerant in challenging circumstances.

Pantola et al. (2017) showed that increasing drought stress negatively impacts seed germination and therefore emergence. Although crop genetics has the biggest effect on drought tolerance, increasing seed vigour also showed better emergence under drier conditions (Pantola et al. 2017). Chloupek et al. (2003) also made use of drought stress as an indication of seed vigour, where better resistance indicated a higher seed vigour and performance potential.

2.2.5 Factors affecting seed vigour

During seed development and storage there are several factors that can influence the vigour of a seed lot. Optimal conditions during development and storage will therefore ensure good seed vigour when the seed is sown. Many factors can influence seed vigour, including seed development environment, genetic constitution, seed maturity, seed size and seed storage environment (Hampton 2002). The stage at which the seed reaches physiological maturity in the field, when seed reach an average seed moisture of 30 – 35% and 40-60% of seeds have changed colour, is when the seed has reached its maximum vigour and future germination potential (Copeland and McDonald 2001). In this section factors that affect seed vigour will be investigated.

2.2.5.1 Seed development environment

Seed vigour may be negatively influenced when unfavourable environmental factors regulate the seed fill stage of the plant (McDonald 1999). The influence of climatic conditions is well recognized for the development of different crops and seed production. Canola crops, spring type as used in South Africa, for instance are grown in cool and wet conditions and will therefore only be sustainable in areas with the optimal climatic conditions. Environmental conditions during crop establishment, crop growth and crop maturation influences subsequent seed yield, germination and vigour potential. After the physiological maturity stage of plant growth, where maximum yield and vigour is expected, the continuous decline in seed vigour is unavoidable (Dornbos 1995a).

Environmental factors contributing to the decrease in seed vigour after physiological maturity include temperature, rainfall and relative humidity (Dornbos 1995b). Alternate wetting and drying during physiological maturity cause damage to the seed and may lead to invasion by microflora and pathogens which can cause seed vigour to be significantly affected through biochemical degradation and physical damage (Fenemore et al. 1999). Heat stress during the flowering stage in canola production results in a reduced number of flowers and also reduces the number and size of the seeds produced per flower (Angadi et al. 2000; Morrison and Stewart 2002). Moisture stress during the seed development stage, before physiological maturity, can also negatively influence the development of seed and result in small seed with low seed vigour (Copeland and McDonald 2001).

2.2.5.2 Soil fertility

Canola is a very adaptable crop which can withstand moderate drought stress and other suppressive factors. Soil fertility affects not only canola's vegetative growth but also has a strong correlation with the reproductive growth, and therefore seed size, seed weight, oil content and thus seed vigour (Austin 1972; Heydecker 1972). The yield and yield quality of canola seed mostly relies on the genetic potential of canola varieties and also environmental conditions affecting growth (Süzer 2014). Application of fertilisers is one of the factors ensuring an increase in seed yield and quality (Vassilina et al. 2012). Modern agronomic cultivation methods of canola suggests a well-balanced fertiliser program including N, P, K, S and B fertilisers to ensure optimal soil fertility conditions and the production of high quality yields (Süzer 2014).

2.2.5.3 Time of seed harvest

Probably the most important factors influencing seed vigour is days after seed maturation, therefore seed has to be harvested as soon as possible after maturation (McDonald 1999). Determining swathing and/or harvest time for canola is a crucial part of production and several methods have been used. Different methods include seed moisture content (optimal at 8-10%), days after anthesis, firmness, average seed colouring and crop colour (Elias and Copeland 2001; Hung 2003). Ultimately canola is considered ready when pods are dry and rattle when shaken and seeds are dark brown in colour and seed moisture is at 8-10% (Berglund et al. 2019).

2.2.5.4 Seed size and mass

In 1972 Walter Heydecker stated that smaller seeds will have less initial potential compared to larger seeds and therefore have an initial disadvantage. Elliott et al. (2007a) and Harker et al. (2015) also confirmed that seed vigour of canola increases with an increase of seed size and therefore large seeds showed improved establishment, shoot weight, biomass and yield. Copeland and McDonald (2001) stated that seed size and weight are influenced by environmental factors during seed development and the stage of development.

2.2.5.5 Post-harvest factors

A high seed moisture content (above 10%) at harvest can result in the seed's respiration process being implemented when stored. The respiration process releases heat and moisture which can create optimal conditions for insect and pathogen development (Hill 1999). Seed deterioration is also caused by fungi that produce enzymes and toxins which negatively affects seed after harvest (Hill 1999).

Fenemore et al. (1999) stated that physical seed damage caused by insects create conditions which are ideal for fungal invasion and possibly cause a loss of seed vigour by initiation of seed deterioration. Damage caused by insect damage and fungal invasion can occur during any stage of seed production, harvest or storage.

High seed moisture during harvest can also result in mechanical damage during harvest and storage since the seed testa is still soft. Mechanical damage cause bruising on the seed which in turn can cause dead tissue in the inner seed structures, which will lead to a loss of seed vigour. Dead tissue not only causes lower seed performance by damaged seed structures but also makes seed more susceptible to rapid deterioration even under optimal storage conditions mostly through fungal infections (Hill 1999; Leeks 2006).

2.3 Conclusion

The importance of canola as a crop has increased substantially in the cereal growing areas of the Western Cape (Mokone 2018; GrainSA 2020). Good seed quality can ensure producers of optimal crop establishment and yields (Bewley and Black 1982). Seed germination percentage is currently the seed quality indicator used for certified seed supplied by seed companies in South Africa. In the literature we can see that the germination percentage in fact shows a quality indication of seed under optimal conditions in laboratory testing, which is almost never the case in the field. Since field conditions can deliver various sub-optimal challenges towards the crop, it is believed that seed vigour is a better estimate of seed quality. As stated by the International Seed Testing Association (2020), seed vigour is an indication of the sum of those properties that determine the activity and performance of seed lots of acceptable germination in a wide range of environments. Since seed vigour is seen as a better estimate of seed quality under a wide range of conditions, it is considered that seed companies should consider some sort of seed vigour indication as well as germination percentage as a quality indicator.

In this study different vigour and seed quality testing methods will be investigated and used to compare 14 different certified canola cultivars available in South Africa, with regards to germination, vigour and field establishment.

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Chapter 3

Establishing general seed quality and emergence potential of available South African canola cultivars

3.1 Introduction

Crop seeds are considered the reproductive units of plants, and therefore seed must be able to germinate, emerge and establish healthy seedlings to develop into productive plants (McDonald and Copeland 1997). Seed size, seed weight and standard germination percentage are all considered to be general seed quality parameters used to indicate seed quality (Hampton 2002; ISTA 2020). Germination percentage is probably the most commonly used quality indicator of seed performance (Hampton 2002). Seed performance as definition is not a single measurable property, but rather a concept associated with several aspects of seed development. The concept of seed performance includes the rate and uniformity of seed germination and emergence and thereafter seedling and plant growth to produce a productive plant to produce a yield (Finch-Savage and Bassel 2015).

A generally assumed norm is that the higher seed quality, the higher seed performance and vigour should be (Elliott et al. 2007b). Thousand seed mass (TSM) and seed size correlates to seed plumpness and is therefore believed to be an indication of seed performance and vigour (Heather and Sieczka 1991). The theory is that the bigger the seed, therefore the higher the thousand seed mass (TSM) and fraction of large seed, the better the performance and vigour of the seed lot will be.

As a general seed quality indication, the TSM for *Brassica napus* (canola) usually ranges between 3-7 grams with the average ranging between 4-5 grams (Elliott et al. 2007a). Normal sized seed for canola is considered too be in the range of 1.7-2.0 mm and seeds smaller than 1.7 mm in diameter is considered small and will most probably have a low performance and vigour (Elliott et al. 2007a). Seeds larger than 2.0 mm is considered large seed and is expected to possess a high seed performance and vigour.

In 2015, Finch-Savage and Bassel stated that seed emergence and crop establishment is in fact the first important factor in any crop production system and has a determining effect on the total yield. Therefore, seed quality needs to be optimal to ensure optimal field emergence and crop performance. Seed needs to emerge as uniformly and abundantly as possible in the field, under a large range of conditions. Seed germination percentage is a laboratory tested quality parameter, under optimal conditions, and is believed to often overestimate the actual field emergence potential of seed lots (Copeland and McDonald 2001).

The aim of this study was to determine general seed quality parameters, such as TSM, seed size fractions and standard germination percentage, of 14 different commonly cultivated canola cultivars of South Africa for the year 2020. These quality parameters were used and compared to glasshouse emergence results to possibly try and determine a field emergence potential. All tested seed quality parameters will also be compared to establish the correlation between each parameter and glasshouse emergence. These results illustrate a one year 'snap-shot' of the quality of canola cultivars in South Africa for the year 2020 and could vary from year to year.

3.2 Materials and methods

Submitted samples (ISTA 2020) from 14 different canola cultivars that were available on the South African retail seed market for the year 2020, were obtained from various seed marketing companies. For the sake of confidentiality, the 14 cultivars were randomly assigned a code number from 1 to 14. In the following results and discussion only the code numbers are going to be presented. All experiments followed a completely randomised design, except for the glasshouse emergence trial which followed a randomised block design.

3.2.1 Thousand seed mass (TSM)

The TSM of 14 different canola cultivars was determined by randomly counting out a thousand seeds from each seed lot's submitted sample (ISTA 2020). The thousand randomly selected seeds were then weighed on a three decimal scale and noted (ISTA 2020). For each seed lot this procedure was repeated five times to establish the mean TSM of each seed lot (ISTA 2020).

Mean TSM was calculated by means of the following formula:

$$Mean\ TSM\ (g) = \frac{(x_1 + x_2 + \cdots + x_n)}{n}$$

where:

x_i = the TSM for the i^{th} repetition;

n = the total number of repetitions

After statistical analysis all the cultivars were assigned a ranking from 1 to 14 according to their TSM results, where a high TSM was considered best.

3.2.2 Seed size fraction

Seeds from each seed lot were sieved though two graded sieves, 1.7 mm and 2.0 mm respectively, which divided seed lots into three size classes. The three size classes were classified as small (<1.7 mm), medium/normal (1.7-2.0 mm) and large (>2.0 mm), similarly to Elliott et al. (2007a) and Giason (2016). Random samples were taken from each seed lot's submitted sample (approx. 30 grams) and sieved. Seeds from each class was then weighed to determine the total weight of the sample and each size fraction's percentage was calculated for each seed lot. This fractioning process was repeated three times to establish the mean for each seed lot and calculated by the same principle as for mean TSM in 3.2.1 for each seed lot per size class.

After statistical analysis all the cultivars were assigned a ranking from 1 to 14 according to overall seed size fractioning results, where a lot with a higher number of large seeds were considered best.

3.2.3 Standard germination

The mean standard germination percentage was determined by randomly selecting a hundred seeds from each seed lot's submitted sample. The one-hundred randomly selected seeds were placed on top of a double layer of moist Whatman filter paper, top paper (TP) method, which was then placed into a sterile petri-dish and closed with a tight-fitting lid (ISTA 2020). The Whatman filter paper was moistened with 5 ml of distilled water. The samples were then placed in a dark, temperature-controlled growth chamber at 20 °C ± 0.5 °C for 16 hours and 30 °C ± 0.5 °C for 8 hours, night/day regime (ISTA 2020). Germination percentages was then assessed after 3, 5 and 7 days, only considering normal seedlings as described by Desai (2004) and ISTA (2020). Seedlings are considered normal when essential structures including an intact primary root, a shoot axis and two cotyledons are visibly formed (ISTA 2020). This process was repeated four times for each seed lot, to establish the mean germination percentage for each seed lot (ISTA 2020). Removal of germinated seeds from petri dishes during counting is necessary, as rooted seeds rapidly remove water from the moist filter paper (Essery et al. 1955).

The equation used for the calculation of mean germination percentage as described by (ISTA 2020):

$$Mean\ Germination\ Percentage\ (\%) = \frac{(a_1 + a_2 + \cdots + a_n)}{n}$$

where:

a_i = the final germination percentage for the i^{th} repetition;

n = the total number of repetitions.

Together with germination percentage, mean germination time (MGT) and germination index (GI) were additional parameters used in this experiment for the interpretation of germination success. These parameters represent the interaction between germination percentage and speed of germination (Kader 2005). Germination results from the one germination parameter may not represent the same seed quality in another parameter, therefore more than one parameter is used to compare results and make a conclusion (Kader 2005).

Mean germination time is a measure of the rate of germination and also the sharpness of the germination peak (Naylor and Syversen 1988; Chen et al. 2013). Mean Germination Time focusses on when the most germination events have occurred and the germination peak is reached (Chen et al. 2013; Soltani et al. 2015). Therefore, lower MGT values indicate faster germination of a population of seeds (Orchard 1977; Kader 2005).

The equation used for the calculation of MGT is as described by Orchard (1977) and Ellis and Roberts (1981):

$$MGT\ (days) = \frac{\Sigma n_i . t_i}{N}$$

where:

n_i = the number of seeds germinated between counting intervals,

t_i = the days from the beginning of the test,

N = the total number of germinated seeds at the end of the test.

The germination index (GI) is another parameter used for analysing, representing and interpreting germination data calculated from germination results (Kader 2005). The GI is believed to be the most comprehensive measurement parameter by combining both the germination percentage, the speed of germination and also magnifies the variation among seed lots in this regard (Kader 2005).

According to Kader (2005) the GI is the best analysis method to describe the germination percentage-speed relationship. In the equation, faster emerging seeds are given a larger proportion and this result in a larger value. Therefore, a high GI will mean more seeds germinated at an earlier stage of germination. Thus, the higher the GI value, the faster seeds germinated and could suggest a high seed field performance and vigour (Moradi Dezfuli et al. 2008).

The germination index (GI) was calculated as described by the Association of Official Seed Analysts (AOSA, 1983):

$$GI = \sum \frac{n_i}{t_i}$$

where:

n_i = the number of seeds germinated between counting intervals,

t_i = the days from the beginning of the test (AOSA 1983).

After statistical analysis all the cultivars were assigned a ranking from 1 to 14 according to mean germination percentage, MGT and GI.

3.2.4 Glasshouse emergence

The emergence was tested under controlled conditions in a glasshouse by means of a pot trial. Ten seeds were randomly selected from each seed lot's submitted sample. The ten randomly selected seeds from each seed lot were then planted in separate round 2-litre plastic pot. Plastic pots were filled with a coarse sand potting medium and filled with water to field water capacity (FWC) before planting. Seeds were planted at a constant depth of 1.5 cm for each seed lot, between 1-2 cm for soils with sufficient moisture as suggested by Harker et al. (2012) and PRF (2018). Pots were watered by hand every second or third day, depending on evaporation conditions, to ensure that water stress was not a limiting factor. The glasshouse ensured controlled conditions with the temperature set on 20-25 °C, night/day regime, throughout the experiment. Inspections and data collection was done every second or third day, when watering was done, and emerged seeds was noted up until 14 days after planting. This process was repeated three times for each seed lot to establish the mean emergence percentage for each seed lot. The trial was laid out as a Randomised block design within the glasshouse.

The equation used for the calculation of mean emergence percentage as described by (ISTA 2020):

$$Mean\ Emergence\ Percentage\ (\%) = \frac{(a_1 + a_2 + \cdots + a_n)}{n}$$

where:

a_i = the final emergence percentage for the i^{th} repetition;

n = the total number of repetitions.

The mean emergence time (MET) and emergence index (EI) were also calculated for the pot trial as additional parameters for analysing the emergence data. Both equations used were the same as used for interpreting the germination results, only with slight terminology changes.

The equation used for the calculation of MET is the same as the equation for mean germination time (MGT) as described by Orchard (1977) and Ellis and Roberts (1981):

$$MET\ (days) = \frac{\Sigma n_i . t_i}{N}$$

where:
n_i = the number of seeds emerged between counting intervals,
t_i = the days from the beginning of the test,
N = the total number of emerged seeds at the end of the test.

The equation used for the calculation of EI is the same as the equation used for the calculation of germination index (GI) as described by the Association of Official Seed Analysts (AOSA, 1983):

$$EI = \sum \frac{n_i}{t_i}$$

where:
n_i = the number of seeds emerged between counting intervals,
t_i = the days from the beginning of the test (AOSA 1983).

Following statistical analysis, the cultivars were assigned a ranking from 1 to 14 according to mean glasshouse emergence percentage, MET and EI.

Correlation and regression analyses were done to establish the relationship between mean germination percentage and mean glasshouse emergence percentage of the 14 canola cultivars tested.

Correlations and regressions are widely used techniques for determining the strength of an association between 2 variables. Correlation provides a unitless measure of association (R), whereas regression provides a means of predicting one variable from the other and describes how much variation is explained between the two variables (R^2) (Crawford 2006).

3.2.5 Overall comparison

All the results of this chapter were compared with one another to, firstly, determine the effect and relationship of all the seed quality parameters on one another and to determine which parameter had the best relationship with seed emergence percentage as predicting variable.

This comparison was done by means of a pairwise multiple regression on all the testing parameters, to determine the relationship of each parameter on one another and specifically on the glasshouse emergence results. The results are represented in a table (Table 3.5) which show the coefficient of determination (R^2) for each interaction combination of all the quality parameters.

After statistical analysis all the cultivars for each experiment was ranked from 1 to 14 according to the testing parameter. The ranking results for each parameter were combined in a table (Table 3.6) whereafter each cultivar received a final overall ranking based on rankings from all the parameters.

The ranking results represent a broad indication of general seed quality on the basis of TSM, seed size fractioning, mean germination, MGT, GI, mean glasshouse emergence, MET and EI. These ranking results represent the overall expected seed vigour and field performance potential of each cultivar compared to the other tested cultivars (Hampton 2002).

3.2.6 Statistical analysis

Statistical analysis was performed by means of STATISTICA version 13.6.0 (TIBCO 2019). All the data was subjected to analysis of variance (ANOVA) to determine if there were any differences between cultivars, cultivar treatments and cultivar performance.

Thousand Seed Mass (TSM), seed size fractioning, mean germination percentage, MGT and GI results all followed a completely randomised design and were all analysed by making use of a one-way ANOVA analysis.

The seed size fractioning results were analysed separately for each size class by means of one-way ANOVA. The one-way ANOVA for the seed size fractioning showed that the assumption of normally distributed residuals was rejected and therefore the Kruskal-Wallis nonparametric test was conducted.

The glasshouse emergence trial was laid out as a randomised block design and was therefore subjected to a two-way ANOVA analysis to determine mean emergence differences between cultivars. The two factors of the two-way ANOVA were the cultivars (treatment) and the blocking factor.

Fisher's least significant difference (LSD) was calculated at the 5% level to compare treatment means. A probability level of 5% was considered significant for all significance tests.

Correlation and regression analyses were done between the mean germination percentage and mean emergence percentage results to investigate the relationship between the two variables (Figure 3.5). Multiple pairwise regressions were also done between all the mean tested general seed quality parameters to investigate the relationships between them and also to determine which quality parameter correlates best with glasshouse emergence of the seed.

3.3 Results

3.3.1 Thousand seed mass (TSM)

Several differences were recorded between the canola cultivars tested with regards to their thousand seed mass (TSM). Cultivars are represented in their three groups, representing their herbicide resistance traits (Table 3.1).

In the conventional group the TSM of Cultivars 6 and 14 were significantly ($p<0.05$) higher than Cultivars 8 and 13 and therefore the highest in this group. Cultivar 13 was significantly ($p<0.05$) higher than Cultivar 8, making Cultivar 8 the cultivar with the lowest TSM in the conventional group. Cultivars 6 and 14 did not significantly differ ($p>0.05$) from one another.

In the Clearfield (CL) group the TSM of Cultivar 1 was significantly ($p<0.05$) the highest in this group. Cultivars 2 and 4 were significantly ($p<0.05$) higher than Cultivar 3, making Cultivar 3 the cultivar with the lowest TSM in the CL group. Cultivars 2 and 4 did not differ significantly ($p>0.05$) from one another.

In the Triazine Tolerant (TT) group the TSM of Cultivar 7 was significantly ($p<0.05$) higher than all the other cultivars in this group. The TSM of Cultivar 10 was significantly ($p<0.05$) lower than Cultivar 7 but also significantly higher ($p<0.05$) than Cultivars 5, 9, 11 and 12. Cultivar 11 had the lowest TSM in this group with Cultivars 5, 9 and 11 also being significantly ($p<0.05$) higher. Cultivars 5, 9 and 12 were scattered between the highest and lowest values.

Some interesting differences were observed in the overall TSM comparison of all the cultivars. The TSM results for each cultivar is described below by dividing results in three categories, high, medium and low performing categories. Cultivars from different categories do not necessarily differ significantly ($p<0.05$), which can be seen in Table 3.1.

Cultivars 1, 7 and 10 were the cultivars with the highest TSM of all the cultivars with values ranging above 5 grams, keeping in mind that Cultivar 10 is a TT variety. Cultivars 8, 9 and 11 had the lowest mean TSM (less than 4 grams). Cultivars 2, 3, 4, 5, 6, 12, 13 and 14 are all scattered between the highest and lowest cultivar, with values ranging between 4 grams and 5 grams.

Table 3.1: Mean thousand seed mass (TSM) results for 14 canola cultivars of South Africa for the year 2020. Cultivar ranking is the rankings given to each cultivar according to their TSM. The cultivars were grouped into three TSM groups (high, medium, low) which is indicated by green, uncoloured and red shadings, respectively

Cultivar no.	Thousand Seed Mass *(g)*	Cultivar Ranking
Conventional Cultivars		
6	4.746^{d}	6
8	3.644^{h}	13
13	4.132^{fg}	10
14	4.502^{de}	8
Clearfield (CL) Cultivars		
1	5.216^{c}	3
2	4.802^{d}	4
3	4.302^{ef}	9
4	4.758^{d}	5
Triazine Tolerant (TT) Cultivars		
5	4.008^{fg}	11
7	5.953^{a}	1
9	3.982^{g}	12
10	5.596^{b}	2
11	3.366^{h}	14
12	4.728^{d}	7

*Distinct letters above values within a column indicate significant ($p<0.05$) differences

3.3.2 Seed size fraction

Several differences were recorded between the different canola cultivars tested with regards to their seed size fractioning. Cultivars are represented in their three groups, representing their herbicide resistance traits. Fractioning is represented in three classes per cultivar and statistically analysed per fraction class (Table 3.2).

The seed size fractioning for each size class is described below by dividing results in three categories, high, medium and low. Cultivars from different categories do not necessarily differ significantly ($p<0.05$), which can be seen in Table 3.2.

In the <1.7 mm size class, which is considered as small seed, Cultivar 8 had the highest ($p<0.05$) percentage of small seeds compared to the other cultivars, namely 4.64%. The fractioning percentages of cultivars 3, 5, and 11 are lower than cultivar 8 but also higher than all the other cultivars, ranging between 2.00% and 3.00%. Cultivars 1, 2, 4, 6, 7, 9, 10, 12, 13 and 14 are all scattered within the smallest percentage and range below 1.50%.

In the 1.7–2.0 mm size class, which is considered as medium/normal seed, Cultivar 11 had the highest percentage ($p<0.05$) of medium/normal seeds compared to the other tested cultivars, with 92.54% medium/normal seeds. The second highest category was classified as 30.00% to 70.00% of medium/normal seeds and included Cultivars 3, 5, 6, 8, 9 and 13. For the 1.7–2 mm size class another category was used to describe the results. The second lowest performing category ranges between 10.00% and 30.00%. Cultivars that are categorised under the second lowest performing category include Cultivars 1, 2, 4, 7, 12 and 14. The cultivar with the lowest percentage ($p<0.05$) of medium/normal seeds is Cultivar 10, with 5.23%.

The fractioning percentages of seeds within the >2.0 mm size class, which is considered as large seed, showed that Cultivars 1, 2, 4, 7, 10, 12 and 14 achieved percentages above 70% and are categorised as the highest performing cultivars within the >2.0 mm size class. Cultivars 3, 6, 9 and 13 had the second highest percentages of large seeds, ranging between 40% and 70%. A second lowest category was also used to describe Cultivars 5 and 8, with values between 20% and 40%. Cultivar 11 had the lowest percentage ($p<0.05$) of large seed with only 4.67%.

Cultivar rankings according to the seed size fractioning showed that cultivar 10 has the largest overall amount of large (>2 mm) sized seeds as well as the least amount of small (<1.7 mm) seeds. Cultivar 8 is ranked last in terms of seed size fractioning and therefore shows that it has the largest overall amount of small (<1.7 mm) sized seeds and one of the lowest amounts of large (>2.0 mm) seeds. Although cultivar 11 had the least number of large seeds it possessed the largest number of medium/normal seeds, which is considered good.

Table 3.2: Mean seed size fractioning percentages within three classes, namely small (<1.7 mm); medium (1.7-2.0 mm) and large (>2.0 mm), of 14 canola cultivars of South Africa for the year 2020. Cultivar ranking is the ranking given to each cultivar according to their overall seed size fractioning percentages across all three classes (1= best and 14= worst). Cells with green and red shading indicate the highest and lowest performing values per column respectively

Cultivar no.	Seed Size Fractioning			Cultivar Ranking
	<1.7 mm	1.7-2.0 mm	>2.0 mm	
Conventional Cultivars		*(%)*		
6	0.55[cd]	31.73[def]	67.72[cd]	8
8	4.64[a]	68.89[b]	26.47[f]	14
13	1.23[c]	34.32[de]	64.44[d]	10
14	0.71[cd]	29.03[ef]	70.26[cd]	7
Clearfield (CL) Cultivars				
1	0.04[d]	15.52[g]	84.44[a]	2
2	0.21[d]	26.71[f]	73.08[c]	6
3	2.25[b]	51.84[c]	45.91[e]	11
4	0.15[d]	18.42[g]	81.43[b]	3
Triazine Tolerant (TT) Cultivars				
5	2.28[b]	66.63[b]	31.09[f]	12
7	0.67[cd]	15.91[g]	83.42[b]	4
9	0.40[cd]	35.17[d]	64.43[d]	9
10	0.13[d]	5.23[h]	94.64[a]	1
11	2.79[b]	92.54[a]	4.67[g]	13
12	0.15[d]	26.35[f]	73.50[c]	5

*Distinct letters above values within a column indicate significant ($p<0.05$) differences

3.3.3 Standard germination

Some differences were recorded between the different canola cultivars tested with regards to their mean germination percentages. Cultivars are represented in their three groups, representing their herbicide resistance traits (Table 3.3). Although cultivars are grouped according to their herbicide resistance traits, it should in fact not influence the mean germination percentage. A visual presentation of the germination percentages of all the cultivars is shown in Figure 3.1. Expected germination percentages, as shown on the product labels, is indicated as a red line on Figure 3.1 at 90%, since all product labels indicate a minimum germination percentage of 90%. The germination percentages as indicated on the product labels are used to compare with the actual germination percentage, as tested. Statistical analysis was done on the actual tested germination percentages to determine differences between cultivars.

The mean germination results for each cultivar are described below by dividing results in high, medium and low performing categories. Cultivars from different categories do not necessarily differ significantly ($p<0.05$), which can be seen in Table 3.3.

Cultivars 1, 2, 5, 6, 7, 10, 11, 12 and 13 recorded the highest ($p<0.05$) mean germination percentages, all ranging above 90%, which agrees with the stated percentages on the product labels. The mean germination percentage of Cultivars 3, 4 and 9 are categorised as the second-best percentages. The mean germination percentage of these cultivars ranged between 70% and 81% and were all less than the minimum percentages stated on the product labels. Cultivars 8 and 14 had significantly ($p<0.05$) lower mean germination percentages than all the other cultivars. The germination percentage of these two cultivars, 35% and 38.75% respectively, are remarkably lower than the percentages stated on the product labels.

In terms of the MGT values the lowest performing category reported MGT values of 5 days and above. The cultivars that fall into this category include Cultivars 2, 5, 8 and 14. The cultivars within the second-best performing category are Cultivars 1, 3, 4, 9, 11 and 13, which showed values between 4 days and 5 days. Cultivars with MGT values below 4 days were considered the best performing cultivars and included Cultivars 6, 7, 10 and 12.

Cultivars 6, 7, 10 and 12 were the cultivars which are considered the highest performing with regards to GI values (30.52, 30.83, 30.53 and 31.57 respectively), and will therefore germinate at a faster rate compared to other cultivars tested. Cultivars 8 and 14 were the cultivars with the lowest GI values at 6.41 and 5.86, respectively. The second-best performing category with regards to GI values were Cultivars 1, 2, 3, 4, 5, 9, 11 and 13, with values ranging from 10 to 30.

Table 3.3: All germination parameters used for assessing 14 canola cultivars of South Africa for the year 2020. Values in brackets indicate the ranking given to each cultivar according to their column parameter (1= best and 14= worst). Cells with green and red shading indicate the highest and lowest performing values per column, respectively

Cultivar no.	Mean Germination Percentage (%)		Mean Germination Time (days)		Germination Index	
Conventional Cultivars						
6	*99.25[a]*	{4}	3.39[d]	{3}	30.52[ab]	{4}
8	*38.75[c]*	{13}	6.18[a]	{14}	6.41[f]	{13}
13	90.75[a]	{9}	4.12[cd]	{5}	24.86[cd]	{6}
14	35.00[c]	{14}	6.15[a]	{13}	5.86[f]	{14}
Clearfield (CL) Cultivars						
1	92.00[a]	{8}	4.22[cd]	{6}	23.46[cd]	{7}
2	94.75[a]	{7}	5.88[a]	{12}	16.96[e]	{11}
3	71.25[b]	{12}	4.47[c]	{7}	17.67[e]	{9}
4	80.25[b]	{10}	4.87[bc]	{10}	17.57[e]	{10}
Triazine Tolerant (TT) Cultivars						
5	98.25[a]	{5}	5.57[ab]	{11}	26.64[bc]	{5}
7	100.00[a]	{1}	3.38[d]	{1}	30.83[a]	{2}
9	71.50[b]	{11}	4.71[bc]	{9}	16.88[e]	{12}
10	99.50[a]	{3}	3.44[d]	{4}	30.53[ab]	{3}
11	98.00[a]	{6}	4.61[c]	{8}	22.26[d]	{8}
12	99.75[a]	{2}	3.28[d]	{2}	31.57[a]	{1}

*Distinct letters above values within a column indicate significant ($p<0.05$) differences

3.3.4 Glasshouse emergence

Some statistical differences were recorded between the different canola cultivars tested with regards to their mean glasshouse emergence percentages. Cultivars are represented in three groups, representing their herbicide resistance traits (Table 3.4). A visual representation of all the cultivars with regards to their emergence percentages is shown in Figure 3.1 and compared to mean germination percentages.

The mean glasshouse emergence results for each cultivar are described below by dividing results in high, medium and low performing categories. Cultivars from different categories do not necessarily differ significantly ($p<0.05$), which can be seen in Table 3.4.

Cultivars 1, 2, 5, 6, 7, 11, 12 and 13 showed higher mean emergence percentages than the rest of the cultivars, ranging between 80% and 100%. The mean emergence percentages of Cultivars 3, 9 and 10 are categorised as the second highest performing cultivars with mean glasshouse emergence percentages ranging between 70% and 80%. Cultivars 4, 8 and 14 was the poorest performing cultivars, with regards to mean glasshouse emergence, achieving percentages of 46.67%, 36.67% and 53.33% respectively.

The MET values, calculated from the glasshouse emergence results, indicate the average emergence performance of the cultivars in terms of emergence speed. Cultivars 8 and 14 achieved the highest MET values, 11.14 days and 10.83 days respectively, and will take the longest to emerge compared to the other cultivars, therefore making up the lowest performing category. The cultivars with the lowest MET values are Cultivars 1, 2, 6, 7, 10, 11, 12 and 13, with values ranging between 6 days and 8 days, which will emerge the fastest compared to the other cultivars. Cultivars 3, 4, 5 and 9 are scattered between the highest and lowest performing cultivars, ranging between 8 days and 9 days.

When comparing the emergence index (EI) results the three cultivars that showed the lowest GI values were Cultivars 4, 8, 9 and 14, with EI values ranging below 1.00. Cultivars 2, 7, 12 and 13 performed the best with regards to EI by recording the highest EI values above 1.50. Ranging between EI values of 1.00 and 1.50 were Cultivars 1, 3, 5, 6, 10 and 11 which were considered the second-best performing cultivars.

The mean germination results and mean glasshouse emergence results are graphically illustrated below (Figure 3.1), and it is clear that certain cultivars were well below the indicated minimum germination percentages on the product labels (90%). Cultivar 4 also showed a substantially lower mean emergence percentage compared to mean germination percentage (not compared statistically). Cultivars 3, 5, 9 and 13 also showed marginally higher mean emergence percentage compared to mean germination percentage.

Table 3.4: All glasshouse emergence parameters used for assessing 14 canola cultivars of South Africa for the year 2020. Values in brackets show the ranking given to each cultivar according to their column parameter (1= best and 14= worst). Cells with green and red shading indicate the highest and lowest performing values per column respectively

Cultivar no.	Mean Glasshouse Emergence (%)		Mean Emergence Time (days)		Emergence Index	
Conventional Cultivars						
6	86.67^{abc}	{7}	7.44^{bcd}	{7}	12.86^{cde}	{7}
8	36.67^{d}	{14}	11.14^{a}	{14}	3.47^{g}	{14}
13	96.67^{ab}	{2}	6.40^{cd}	{4}	15.88^{ab}	{2}
14	53.33^{d}	{12}	10.83^{a}	{13}	4.93^{g}	{13}
Clearfield (CL) Cultivars						
1	83.33^{abc}	{8}	6.64^{cd}	{6}	13.58^{bcd}	{6}
2	93.33^{abc}	{4}	6.37^{cd}	{3}	15.22^{abc}	{4}
3	76.67^{c}	{10}	8.19^{bc}	{10}	10.20^{ef}	{10}
4	46.67^{d}	{13}	8.73^{b}	{12}	5.73^{g}	{12}
Triazine Tolerant (TT) Cultivars						
5	100^{a}	{1}	8.17^{bc}	{9}	12.93^{cd}	{8}
7	96.67^{ab}	{3}	6.17^{d}	{1}	16.45^{a}	{1}
9	76.67^{c}	{11}	8.51^{b}	{11}	9.30^{f}	{11}
10	80.00^{bc}	{9}	7.53^{bcd}	{8}	11.19^{def}	{9}
11	90.00^{abc}	{6}	6.40^{cd}	{5}	14.55^{abc}	{5}
12	93.33^{abc}	{5}	6.36^{cd}	{2}	15.39^{abc}	{3}

*Distinct letters above values within a column indicate significant ($p<0.05$) differences

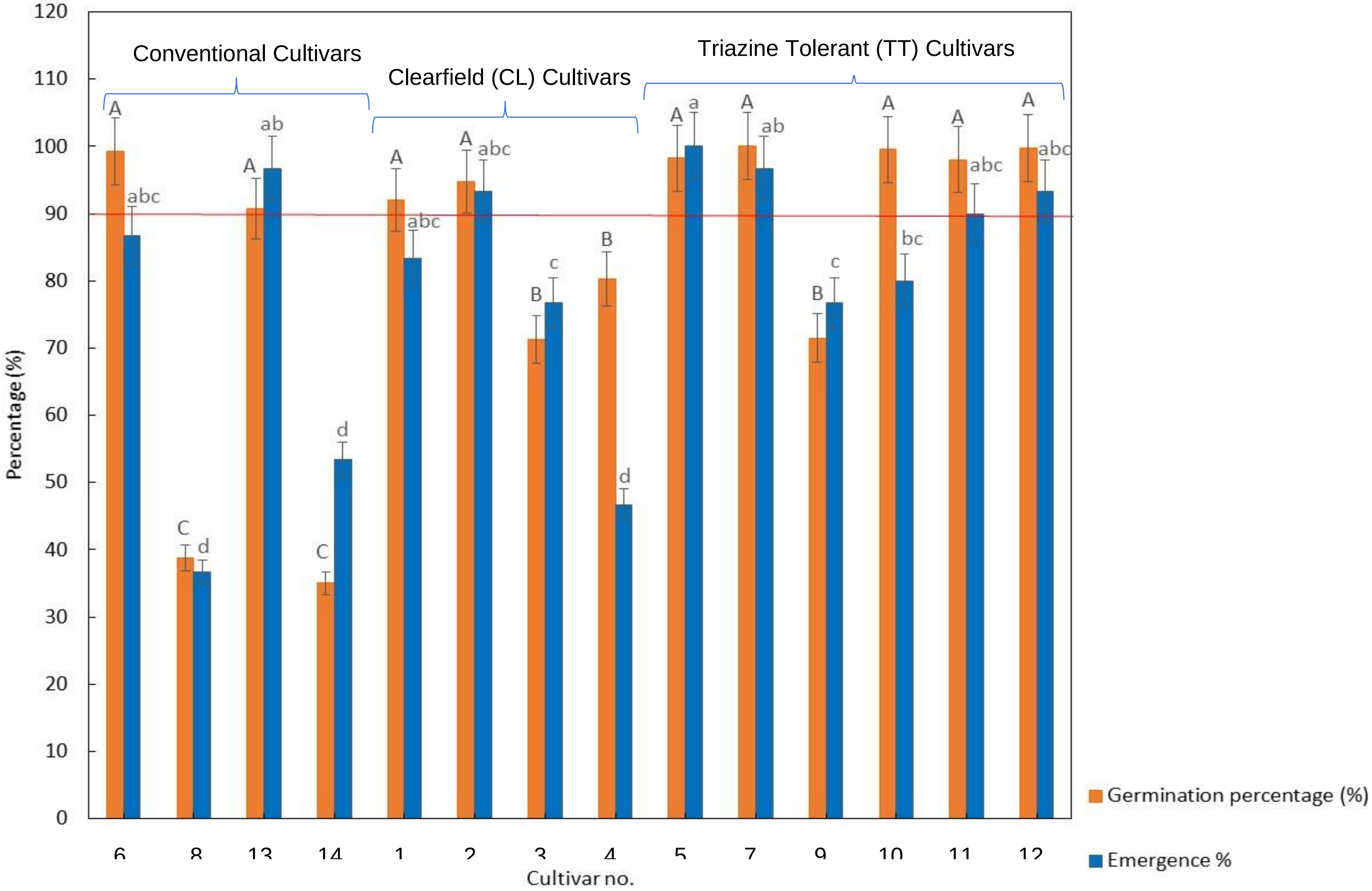

Figure 3.1: Mean germination percentages and mean glasshouse emergence percentages of 14 commonly cultivated canola cultivars of South Africa for the year 2020. Distinct uppercase letters indicate significant (p<0.05) differences between mean germination percentages and distinct lowercase letters indicate significant (p<0.05) differences between mean emergence percentages. Error bars indicate 95% confidence interval within each data series. Red line (90%) indicates the expected germination percentage as indicated on product labels

In Figure 3.2 the correlation and regression graph between mean germination percentage and mean glasshouse emergence percentage indicate the correlation coefficient (R-value) and coefficient of determination (R^2-value). The R-value for the correlation, was 0.82749 which is considered a strong positive correlation (R>0.7) in statistical terms (Kozak 2009). The coefficient of determination (R^2) value for the regression was 0.68474. This means that 68.47% of variation in percentage emergence can be explained by the variation in percentage germination. The R^2 value represents a moderate relationship between mean germination percentage and mean glasshouse emergence percentage (Moore et al. 2013)

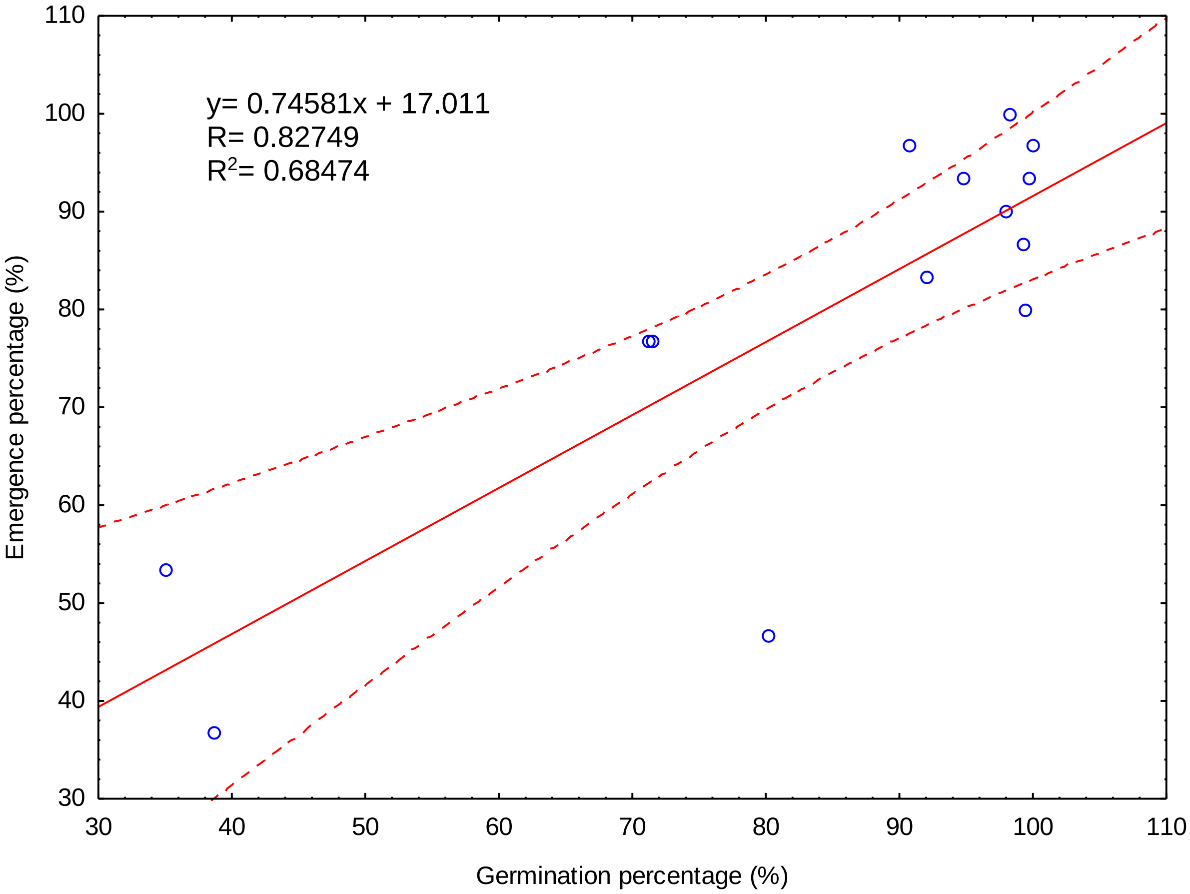

Figure 3.2: Relationship between mean germination percentage (X) and mean glasshouse emergence percentage (Y) of 14 commonly cultivated canola cultivars of South Africa for the year 2020. Correlation was calculated at a 95% confidence interval as indicated by the broken lines.

3.3.5 Overall comparison

Mean germination percentage, when comparing the mean coefficient of determination (R^2) values in Table 3.5, showed the best relationship with mean glasshouse emergence, with R^2 equal to 0.68474. This indicates that 68.474% of variation is described and indicates a moderate relationship ($0.5 < R^2 < 0.7$), according to Moore et al. (2013). The R^2 values of MET and EI, when compared to mean glasshouse emergence, also indicate strong relationships but was not noted as indication parameters for indicating emergence potential. Thousand Seed Mass has a strong relationship with seed size fractioning, but a very poor relationship with mean glasshouse emergence, and mean germination percentage. Therefore, the mean germination percentage is in fact the best general seed quality indicator for glasshouse emergence.

The results from all rankings, as ranked after each test, showed some interesting results. Cultivars 7, 10 and 12 had the best rankings across all the tested parameters and therefore had the best general seed quality. These three cultivars are all from the TT group.

Cultivars 8 and 14 were the cultivars that recorded the lowest performance throughout all the parameters tested. These two cultivars therefore have the lowest general seed quality compared to other cultivars tested.

Table 3.5: Coefficient of determination (R^2) values for each pairwise interaction combination of all the general seed quality parameters used for assessing 14 canola cultivars of South Africa for the year 2020. Cells with red shading indicate the highest R^2 values within the glasshouse emergence percentage parameter

Seed Quality Parameters	TSM	Seed Size Fraction (<1.7mm)	Seed Size Fraction (1.7-2.0mm)	Seed Size Fraction (>2.00mm)	Germination Percentage	MGT	GI	Glasshouse Emergence Percentage	MET	EI
Thousand Seed Mass (TSM)	**1**	0.594	0.821	0.821	0.118	0.216	0.176	0.017	0.083	0.034
Seed Size Fraction (<1.7mm)	0.594	**1**	0.718	0.743	0.178	0.212	0.173	0.095	0.195	0.108
Seed Size Fraction (1.7-2.0mm)	0.821	0.718	**1**	0.999	0.036	0.178	0.083	0.001	0.042	0.010
Seed Size Fraction (>2.00mm)	0.821	0.743	0.999	**1**	0.041	0.183	0.089	0.003	0.048	0.013
Germination Percentage	0.118	0.178	0.036	0.041	**1**	0.463	0.831	0.685	0.823	0.737
Mean Germination Time (MGT)	0.216	0.212	0.178	0.183	0.463	**1**	0.737	0.260	0.437	0.340
Germination Index (GI)	0.176	0.173	0.083	0.089	0.831	0.737	**1**	0.590	0.620	0.608
Glasshouse Emergence Percentage	0.017	0.095	0.001	0.003	0.685	0.260	0.590	**1**	0.620	0.608
Mean Emergence Time (MET)	0.083	0.195	0.042	0.048	0.823	0.437	0.620	0.620	**1**	0.608
Emergence Index (EI)	0.034	0.108	0.010	0.013	0.737	0.340	0.608	0.608	0.608	**1**

Table 3.6: Overall ranking results as ranked after each general seed quality test used for assessing 14 canola cultivars of South Africa for the year 2020

Cultivar no.	Thousand Seed Mass	Seed Size Fractioning	Germination Percentage	Mean Germination Time	Germination Index	Mean Glasshouse Emergence Percentage	Mean Emergence Time	Emergence Index	Average Ranking Value	Overall Ranking
Conventional Cultivars										
6	6	8	4	3	4	7	7	7	5.75	4
8	13	14	13	14	13	14	14	14	13.63	14
13	10	10	9	5	6	2	4	2	6.00	6
14	8	7	14	13	14	12	13	13	11.75	13
Clearfield (CL) Cultivars										
1	3	2	8	6	7	8	6	6	5.75	5
2	4	6	7	12	11	4	3	4	6.38	7
3	9	11	12	7	9	10	10	10	9.75	11
4	5	3	10	10	10	13	12	12	9.38	10
Triazine Tolerant (TT) Cultivars										
5	11	12	5	11	5	1	9	8	7.75	8
7	1	4	1	1	2	3	1	1	1.75	1
9	12	9	11	9	12	11	11	11	10.75	12
10	2	1	3	4	3	9	8	9	4.88	3
11	14	13	6	8	8	6	5	5	8.13	9
12	7	5	2	2	1	5	2	3	3.38	2

3.4 Discussion

3.4.1 Thousand seed mass (TSM)

According to Elliott et al. *(*2007a) the TSM for *Brassica napus* (canola) generally ranges from 3 grams to 7 grams with the average being 4-5 grams. The mean TSM of three of the cultivars revealed a mass lower than the average of 4 grams for canola as reported by Elliott et al. (2007a) and two cultivars had TSM above 5 grams (Table 3.1).

Cultivars 8, 9 and 11 were the three cultivars with the lowest TSM compared to all the cultivars tested. These cultivars reported mean TSM values below the average of 4 grams. Although the TSM of Cultivars 9 and 11 are considered below the average TSM for canola, it is not too concerning since these cultivars are in the Triazine Tolerant (TT) group and are still above the overall lower range of 3 grams. Triazine Tolerant (TT) varieties have a lower yield potential than the other varieties and therefore possess a lower TSM overall and will grow into a smaller plant with a lower yield (Robertson et al. 2002).

The cultivar raising the most concern is Cultivar 8, a conventional variety, which recorded a TSM below 4 grams. Conventional varieties usually possess a high yield and growth potential which should be reflected in a larger TSM (GRDC 2015; PRF 2018).

According to Heydecker (1972) and Elliott et al. (2007b), smaller seeds will possess a lower seed vigour and most probably not perform as well as bigger seeds with a higher seed vigour, especially under less optimal conditions.

Cultivar 7 had the highest ($p<0.05$) TSM value (5.95 grams) of all the cultivars and is expected to deliver satisfying results in further testing. Cultivar 1 and 10 also reported a TSM value above the average of 5 grams for canola. Cultivars 7 and 10 are both grouped into the TT variety which is excellent for TT cultivars.

All the remaining cultivars recorded TSM values between 4 and 5 grams, which according to Elliott et al. (2007a) is considered the normal TSM for canola seed.

3.4.2 Seed size fraction

Elliott et al. (2007b) stated that smaller seeds will most probably have a low performance potential and seed vigour. Small seeds will therefore not necessarily deliver the best results, especially under less optimal conditions. Therefore, the highest percentage of large seeds (>2.0 mm) and the lowest percentage of small seeds (<1.7 mm) is preferable.

Cultivar 10 had the highest ranking of all the cultivars with regards to its seed size fractioning, possessing the highest percentage of large seeds and one of the lowest percentages of small seeds. Cultivar 8 on the other hand had the lowest ranking of all the cultivars with regards to its seed size fractioning, possessing one of the lowest amounts of large seeds and significantly ($p<0.05$) had the largest number of small seeds. Cultivar 11 had the second lowest ranking but is not too concerning since it still possesses 92.54% medium (1.7-2.0 mm) seeds, which is considered normal seed size. Cultivar 11 is also a TT-cultivar, and is expected to have somewhat smaller seeds compared to CL and conventional cultivars (Robertson et al. 2002).

Cultivar 10 is grouped as a TT-cultivar, which is exceptional for a TT-cultivar to possess the highest number of large seeds compared to the other cultivars. Cultivar 8 is concerning as it is a conventional cultivar which should mean that it should possess a large yield and growth potential and have more large seeds (Robertson et al. 2002).

3.4.3 Standard germination

A low germination percentage suggests that under optimal conditions the seed quality of a certain seed lot is questionable since physiological seed deterioration has possibly begun (Hampton and Coolbear 1990; Hampton and Hill 1990). According to Hampton and Coolbear (1990), a seed lot's germination percentage should be above a certain norm (90%). The minimum government proscribed norm for certified canola seed in South Africa is 70% however (Didiza 2002).

According to the product labels, all the seed lots tested had a minimum germination percentage above 90%, which is acceptable and corresponds to the norm as suggested by Hampton and Coolbear (1990) and is above the minimum certification norm in South Africa (Didiza 2002).

The results from the germination test for each cultivar in fact showed some concerning results with regards to mean germination percentage. Cultivars 8 and 14 had the lowest ($p<0.05$) germination percentage compared to the other cultivars, with 38.75% and 35.00% respectively. The germination percentage of Cultivars 8 and 14 showed that physiological deterioration had most probably already started a while before, according to Hampton and Hill (1990). The germination percentage as tested is also markedly lower than the reported germination on the product label.
Cultivars 3 and 9 showed germination percentages of 71.25% and 71.50% respectively. These germination percentages are also lower than the 90% as indicated on the product label and as the indicated norm by Hampton and Coolbear (1990). However, these two cultivars are still above the minimum certification germination for canola as stated in the plant improvement act of 1976 (ACT No. 53 OF 1976) (Didiza 2002). Cultivar 4 also did not differ significantly ($p>0.05$) from Cultivars 3 and 9 although it had a mean germination percentage of 80.25%, which is still lower than indicated on the product label. These germination values suggest that physiological seed deterioration had most probably started recently (Hampton and Hill 1990).

All the other cultivars reported germination percentages above the norm of 90% and correspond with the product labels. These cultivars are expected to perform well in further testing whereas the lower performing cultivars are believed to have low vigour and will most probably result in lower performance.

ISTA (2020) defines seed vigour as the sum of those properties that determine the activity and performance of seed lots of acceptable germination in a wide range of environments. ISTA's definition does in fact not consist of a single measurable property but rather a concept associated with aspects of seed performance that include rate and uniformity of seed germination (ISTA 2020).

Mean germination time (MGT) and germination index (GI) are both representations of germination speed and is a measure of the rate of germination and also the sharpness of the germination peak at different stages (Naylor and Syversen 1988; Chen et al. 2013). Therefore, the lower the MGT and the higher the GI values respectively, the faster seeds germinated and could suggest a high seed vigour (Moradi Dezfuli et al*.* 2008).

The MGT and GI rankings of Cultivars 8 and 14 were overall the highest and lowest, respectively, which means that they took the longest to reach their germination peak. The slower germination of these two cultivars can possibly indicate that that these cultivars may have low seed vigour and will perform poorly under field condition, which will be assessed in later chapters.

3.4.4 Glasshouse emergence

Cultivars 1, 2, 5, 6, 7, 11, 12 and 13 all showed the highest mean emergence percentages and these ranged between 80 and 100%. Compared to mean germination percentages all the best performing cultivars showed similar performance except for Cultivar 10 (Figure 3.1). Cultivar 10 had a mean germination percentage of 99.50% and reported a mean emergence percentage of 80%. Although there is not a major difference between the germination and emergence of Cultivar 10, it showed that even under only slightly more challenging conditions, performance was lower. This might be an indication of slightly lower vigour in Cultivar 10 than in the other high performing cultivars. This slight decline in mean emergence percentage of some of the other cultivars can possibly be a sign of slightly lower seed vigour but can more likely be ascribed to the random nature of the experiment, where different randomly selected seed is tested for each experiment. This can probably also explain most cases where there was a higher emergence percentage than germination percentage such as in the case of Cultivars 3, 5, 9 and 13. However, the vigour of the seeds will be tested extensively in Chapter 4.

Cultivar 4, 8 and 14 showed the lowest performance with regards to emergence testing, considering all emergence parameters. The emergence percentage of Cultivars 8 and 14 correspond to their germination result where these two cultivars also had the poorest performance. Cultivar 4 however, performed remarkably worse in the emergence experiment than in the germination experiments, declining from an 80.25% mean germination percentage to a 46.67% mean emergence percentage. This decrease in emergence percentage can possibly be explained by a low seed vigour where seed will perform worse under less favourable conditions. All these cultivars are believed to have low seed vigour and are not expected to perform well under field conditions (Hampton and Hill 1990).

Cultivar 14 showed a much lower mean germination percentage compared to mean emergence percentage (Figure 3.1). In Table 3.3, Cultivar 14 revealed a very slow germination rate and might not have reached its peak of germination after 7 days. Since ISTA (2020) stated that the final count should be done at 7 days and also for consistency across the experiment the experiment time for Cultivar 14 was not extended. Due to these facts, it is believed that Cultivar 14 might have had a somewhat higher mean germination percentage if it had been allowed more time to germinate and this possibly explains the difference between mean germination percentage and mean glasshouse emergence percentage. The very slow rate of germination is however still a concerning indication of possible low seed vigour (Kader 2005; Moradi Dezfuli et al*.* 2008).

The MET results showed that Cultivars 6, 10 and 12 emerged at a slower rate as predicted from the mean germination time (MGT), compared to the other cultivars. Cultivars 2, 5 and 11 in fact performed a bit better with regards to MET, compared to the other cultivars. The better or worse performance can possibly be explained by high and low seed vigour. The EI results showed an increase for Cultivars 2, 11 and 13 and a decrease for Cultivars 4 and 10 compared to GI results.
Comparing all the emergence parameters, generally Cultivars 4 and 10 performed worse for all the germination parameters. This poorer performance can possibly be explained by a lower seed vigour according to Hampton and Hill (1990), and it is believed that they will perform poorly compared to the other cultivars in field trials.

The R-value for the correlation between mean germination percentage and mean glasshouse emergence percentage was 0.82749 (Figure 3.2) which is considered a strong positive correlation ($R>0.7$) in statistical terms (Kozak 2009). The coefficient of determination (R^2) value for the regression was 0.68474. This means that 68.474% of variation is described and therefore the emergence percentage can be predicted from the germination percentage with 68.474% certainty (Chin 1998; Hair et al. 2012). Therefore, we can conclude that for this study a moderate relationship between mean germination percentage and mean glasshouse emergence percentage was observed (Chin 1998; Hair et al. 2012; Moore et al. 2013).

3.4.5 Overall comparison

Results from the multiple pairwise regression table (Table 3.5) compared all the testing parameters to determine the relationship of each parameter to the glasshouse emergence results as well as to one another.

Table 3.5 reports all the coefficient of determination (R^2) values for each combination of all the quality parameters. Mean germination percentage has the strongest relationship with mean glasshouse emergence, with regards to R^2. The R^2 value, of 0.68474, shows a moderate effect ($0.5 < R^2 < 0.7$) according to Moore et al. (2013). Therefore, the mean germination percentage is in fact the best general seed quality indicator for estimating glasshouse emergence in this study although it is not a strong indicator.

Table 3.6 showed that after taking all the rankings of tested parameters into consideration, Cultivars 7, 10 and 12 showed the best overall rankings. Since these cultivars performed best over all the tested parameters it suggests that these cultivars have the best seed quality and according to Hampton (2002) they are believed to have the highest seed vigour and field performance potential.

Cultivars 8 and 14 were the lowest performing cultivars throughout all testing parameters, having the lowest overall rankings and are therefore believed to possess low seed quality, seed vigour and field emergence potential (Hampton 2002).

3.5 Conclusion

The general seed quality results are crucial information to producers and should therefore be as accurate and reliable as possible. Producers, in turn, rely on the accurate indication of TSM to calculate accurate seeding densities. All general seed quality indicators also ensure producers of high-quality seed and enables them to get an indication of possible field emergence potentials.

From the findings in this chapter it can be concluded that mean germination percentage is the general seed quality parameter that correlates best with seed glasshouse emergence potential and is the best indicator of seed emergence potential, although not a strong indicator. Referring to this principle it is believed that Cultivars 1, 2, 5, 6, 7, 10, 11, 12 and 13, which showed the highest mean germination percentages, all have high field emergence potentials and Cultivars 8 and 14 will have the lowest field emergence potentials.

Cultivars 7, 10 and 12 proved to be the best performing cultivars with regards to overall general seed quality. Overall, Cultivars 8 and 14 reported the lowest performance according to general seed quality and emergence results and are expected to performance poorly in following chapters where seed vigour and field performance will be investigated.

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Chapter 4

Comparing seed vigour of available South African canola cultivars by exposing them to certain stress related vigour testing

4.1 Introduction

The practice of seed vigour testing as a regularly used seed quality indicator has yet to become established in the South African seed industry as in many other parts of the world, especially on canola (Van De Venter and Lock 2013). No comparison can therefore be made between canola cultivars with regards to seed vigour to estimate field performance potential. The concept of seed performance includes the rate and uniformity of seed germination and emergence and thereafter seedling and plant growth to produce a productive plant to produce a yield (Finch-Savage and Bassel 2015).

Chronological age, certification class and germination values of seed lots are often the same, but differ significantly in field establishment performance and germination after storage (Hampton 1999). These performance differences are suspected to be a result of differences in seed vigour. Germination testing fails to fully take into account the effect of the ongoing seed deterioration process, physical seed damage and quality factors which can be detected by seed vigour testing (Elias and Copeland 2001).

ISTA (2020) defines seed vigour as, “the sum of those properties that determine the activity and performance of seed lots of acceptable germination in a wide range of environments”. Therefore, a seed lot with high vigour is considered seed that is able to potentially perform well, in terms of establishment, growth and yield, even under less-optimal environmental conditions (ISTA 2020).

Seed vigour testing can be done to provide separations between low and high vigour canola seed lots. These results are used to obtain valuable information with regards to the establishment quality and potential of seed lots in a wide range of environments, as well as the storage potential of seed lots (ISTA 2020). Hampton (1993) stated that seed vigour testing should be able to provide a more sensitive index of seed quality compared to the standard germination test, and consistently rank seed lots in terms of potential field performance.

The aim of this study is to incorporate accelerated ageing (AA), planting depth and drought stress as vigour testing methods to determine seed vigour and field performance potential differences of 14 different canola cultivars of South Africa for the year 2020. The results will be used in Chapter 5 to test which vigour testing parameter correlates best with field performance. This study only encompasses data for seed from the year 2020 to illustrate a one year ‘snap-shot’ of the quality of canola cultivars in South Africa and could vary from year to year.

4.2 Materials and methods

Submitted samples (ISTA 2020) from 14 different canola cultivars, that were available on the South African retail seed market for the year 2020, were obtained from various seed marketing companies. For the sake of confidentiality, the 14 cultivars were randomly assigned a code number from 1 to 14. In the following results and discussion only the code numbers are going to be mentioned.

4.2.1 Accelerated ageing (AA)

The accelerated ageing procedure is a seed vigour testing method used by various scientists across the world, on several different crops (Hampton and Tekrony 1995; Elias and Copeland 2001; Marcos-Filho 2015; Betânia et al. 2020). The accelerated ageing test is therefore used as a vigour test in this study to establish differences in seed vigour of canola seed lots, by means of germination and emergence testing after ageing.

The accelerated ageing (AA) test was conducted by ageing seeds from different canola cultivars generally cultivated in South Africa. Four samples of approximately 10 grams each, were randomly collected from each seed lot's submitted sample for the AA procedure. Each sample was then aged for 0, 24, 48 and 72 hours, respectively, using the wire-mesh tray method as described by Hampton and Tekrony (1995), Elias and Copeland (2001) and ISTA (2020). The '0 hour' treatment was kept separate since no ageing was required.

The wire-mesh ageing method makes use of an accelerated ageing (AA) box. The AA box consists of an outer plastic box with a tight-fitting lid, 11.0 x 11.0 x 3.5 cm (length x width x depth), into which a plastic wire-mesh tray is placed (Figure 4.1).

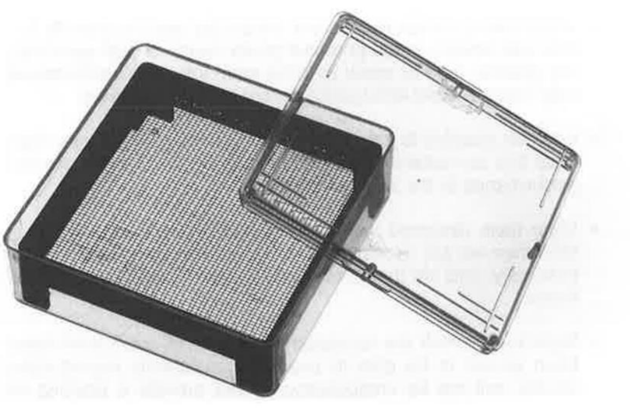

Figure 4.1: Accelerated ageing (AA) box with outer plastic box and plastic wire-mesh tray inside (Tekrony 1993)

Fifty millilitres (50 ml) of distilled water was placed in the plastic AA box, below the wire-mesh tray. One single layer of randomly sampled seed (±10 grams) from each seed lot's submitted sample was spread out evenly on the wire-mesh tray, repeated three times for the 24, 48 and 72 hour treatments per seed lot. The wire-mesh tray was then carefully placed into the inner ageing chamber, making sure no contact was made between the water and the seeds, before closing the plastic AA box with a tight-fitting lid. The plastic AA box with the wire-mesh tray, distilled water and seed was then positioned into a dark, temperature-controlled growth chamber at 42 °C ± 0.5 °C. The AA boxes were then removed after the needed incubation times (24, 48 or 72 hours) and seeds were air-dried before further testing for mean germination and emergence.

4.2.1.1 Standard germination testing after accelerated ageing (AA)

Following the AA procedure, seeds from each aged treatment (0, 24, 48 and 72 hours) were subjected to a standard germination test where higher vigour seed lots are expected to tolerate this AA procedure better than lower vigour seed lots, thereby producing a higher percentage of normal seedlings (Baalbaki et al. 2009). The germination test followed a completely randomised design.

The standard germination percentage was determined by randomly selecting a hundred seeds from each seed lot's aged treatments. The one hundred randomly selected seeds were placed on a double layer of Whatman filter paper, top paper (TP) method (ISTA 2020), which was then placed into a sterile petri-dish and closed with a tight-fitting lid. The Whatman filter paper was moistened with 5 ml of distilled water. The petri dishes were then placed in a dark, temperature-controlled growth chamber set at 20 °C ± 0.5 °C for 16 hours and 30 °C ± 0.5 °C for 8 hours, night/day regime (ISTA 2020). Germination percentage was then assessed after 3, 5 and 7 days only counting "normal" seedlings as described by Desai (2004) and ISTA (2020). Seedlings are considered normal when essential structures including an intact primary root, a shoot axis and two cotyledons are visible (ISTA 2020). The removal of germinated seeds was necessary, since rooted seeds rapidly removed water from the moist filter paper (Essery et al. 1955). This process was repeated four times for each seed lot's aged treatment, to establish a mean germination percentage for each seed lot's aged treatment (ISTA 2020).

The equation used for the calculation of mean germination percentage as described by (ISTA 2020):

$$Mean\ Germination\ Percentage\ (\%) = \frac{(a_1 + a_2 + \cdots + a_n)}{n}$$

where:

a_i = the germination percentage for the i^{th} observation;

n = the total number of repetitions.

Mean germination time (MGT) and germination index (GI) are additional parameters used for analysing, representing and interpreting germination data calculated from germination results (Kader 2005). These parameters represent the interaction between germination percentage and speed of germination (Kader 2005). Germination results from the one germination parameter may not represent the same seed quality in another parameter, therefore more than one parameter is used to compare results and reach a conclusion (Kader 2005).

The MGT is a method of measuring the rate of germination and also the sharpness of the germination peak (Naylor and Syversen 1988; Chen et al. 2013). Mean Germination Time determines when the most germination events have occurred and the germination peak is reached (Chen et al. 2013; Soltani et al. 2015). Therefore, lower MGT values indicate faster germination of a population of seeds (Orchard 1977; Kader 2005)

The equation used for the calculation of MGT is as described by Orchard (1977) and Ellis and Roberts (1981):

$$MGT\ (days) = \frac{\Sigma n_i . t_i}{N}$$

where:

n_i = the number of seeds germinated between counting intervals,

t_i = the days from the beginning of the test,

N = the total number of germinated seeds at the end of the test.

Germination index (GI) is believed to be the most comprehensive measurement parameter by combining both the germination percentage, the speed of germination and also magnifies the variation among seed lots in this regard (Kader 2005). According to Kader (2005) GI is the best analysis method to describe the germination percentage-speed relationship. In the equation, faster germinating seeds will have a smaller dividing factor and results in a larger value. Therefore, a high GI will mean more seeds germinated at an earlier stage of germination. Thus, the higher the GI value is, the faster seeds germinate and could suggest a high seed field establishment performance and vigour (Moradi Dezfuli et al. 2008).

The germination index (GI) was calculated as described by the Association of Official Seed Analysts (AOSA, 1983):

$$GI = \sum \frac{n_i}{t_i}$$

where:

n_i = the number of seeds germinated between counting intervals,

t_i = the days from the beginning of the test (AOSA 1983).

After statistical analysis all the cultivars were assigned a ranking from 1 to 14 according to mean germination percentage, MGT and GI for aged treatments.

4.2.1.2 Emergence testing after accelerated ageing (AA)

According to Baalbaki et al. (2009) and Marcos-Filho (2015) seed lots with high seed vigour will tolerate the AA procedure better than low vigour seed lots and that will be reflected in the emergence of seedlings after planting the seed. Therefore, seed lots with high seed vigour will have higher mean emergence percentages over all the aged treatments, with lower difference values between the aged treatments.

The emergence for each seed lot was determined, after ageing, by randomly selecting ten seeds from each seed lot's aged treatment. The ten randomly selected seeds from each treatment were planted in separate 2-litre plastic pots. Plastic pots were filled with a coarse sand potting medium and filled with water to field water capacity (FWC) before planting. Seeds were planted at a constant depth of 15 mm for each seed lot, conforming to planting depths of between 10 and 20 mm for soils with sufficient moisture as suggested by Harker et al. (2012) and PRF (2018). Pots were watered by hand every second or third day, depending on evaporation conditions, to ensure that water stress was not a limiting factor. The glasshouse ensured controlled conditions with the temperature set on a constant 20-25 °C throughout the trial. The trial was laid out as a randomised block design in the glasshouse. Inspections and emergence counts were done every second or third day, when watering was done, and emerged seeds was noted up until 14 days after planting. This process was repeated three times for each seed lot treatment to establish a mean emergence percentage for each seed lot's aged treatment.

The equation used for the calculation of mean emergence percentage as described by (ISTA 2020):

$$Mean\ Emergence\ Percentage\ (\%) = \frac{(a_1 + a_2 + \cdots + a_n)}{n}$$

where:

a_i = the final emergence percentage for the i^{th} repetition.

n = the total number of repetitions.

The mean emergence time (MET) and emergence index (EI) was also calculated for the pot trial as additional parameters for analysing, representing and interpreting the emergence data. Both equations are the same as used for interpreting the germination results, only with slight terminology changes.

The equation used for the calculation of MET is the same as the equation for mean germination time (MGT) as described by Orchard (1977) and Ellis and Roberts (1981):

$$MET\ (days) = \frac{\Sigma n_i . t_i}{N}$$

where:

n_i = the number of seeds emerged between counting intervals,

t_i = the days from the beginning of the test,

N = the total number of emerged seeds at the end of the test.

The equation used for the calculation of EI is the same as the equation used for the calculation of germination index (GI) as described by the Association of Official Seed Analysts (AOSA, 1983):

$$EI = \sum \frac{n_i}{t_i}$$

where:

n_i = the emergence percentage increase between counting intervals,

t_i = the days from the beginning of the test (AOSA 1983).

After statistical analysis all the cultivars were assigned a ranking from 1 to 14 according to mean emergence percentage, MET and EI for aged treatments.

4.2.2 Planting depth

In 2019, de Oliveira et al. (2019) made use of a planting depth trial as a stress factor for vigour testing and it was also done in this trial as a seed vigour test. Differences in seed vigour can be established by assessing emergence results of seeds sown at different depths, especially at deeper than normal planting depths which will serve as a stress factor for seeds. Canola seed is normally planted at depths of 10-30 mm (Harker et al. 2012; Karow 2014; PRF 2018).

Fourteen different canola cultivars were used for the planting depth trial which was done as a pot trial in a glasshouse. Ten seeds were randomly selected from each seed lot's submitted sample and planted separately in 2-litre plastic pots at four different depths, 10 mm, 20 mm, 40 mm and 60 mm. Plastic pots were filled with a coarse sand potting medium and filled with water to field water capacity (FWC) before planting. Pots were watered by hand every second or third day, depending on evaporation conditions, to ensure that water stress was not a limiting factor. The glasshouse ensured controlled conditions with the temperature set on a constant 20-25 °C night/day temperature throughout. The trial was laid out as a randomised block design. Inspections was done every second or third day, when watering was done, and emerged seeds were noted until 21 days after planting. This process was repeated three times for each seed lot to establish a mean emergence percentage for each seed lot at each planting depth.

Mean emergence percentage, mean emergence time and emergence index was calculated making use of the same formulas as presented in Section 4.2.1.2 above in the emergence pot trial.

After statistical analysis all the cultivars were assigned a ranking from 1 to 14 according to mean emergence percentage, MET and EI for planting depths.

4.2.3 Drought stress

Drought stress resistance gives an indication of seed vigour where seed lots with higher seed vigour will resist drought stress better and show a higher emergence percentage compared to seed lots with low vigour (Chloupek et al. 2003; Pantola et al. 2017). In this trial, each seed lot's resistance towards drought stress was tested by means of a pot trial in a temperature-controlled glasshouse.

The treatment used to simulate drought stress was an addition of a 0.2% Polyethylene glycol 6000 (PEG-6000) solution with an osmotic potential of about -500 KPa, which is believed to cause moderate drought stress conditions and simulates 50% field water capacity (FWC) (Michel and Kaufmann 1973). The PEG-6000 solution was made up by mixing 200 g of PEG-6000 per 1000 ml of distilled water (200 g PEG-6000 kg^{-2} H_2O). The solution was added by filling each pot up to FWC with the solution at each watering.

The emergence percentages for each seed lot in the drought stress trial was tested by planting ten randomly selected seeds from each seed lot's submitted sample. The ten randomly selected seeds from each seed lot were planted in separate round plastic 2-litre pots filled with a course-sand medium. All seeds were planted at a constant depth of 15 mm, the same depth as for the emergence trial in chapter 3. Pots were filled to FWC with the PEG-6000 solution every third day to ensure 50% FWC simulation. The glasshouse ensured a controlled environment with the temperature set on a constant 20-25 °C night/day temperature throughout and the trial was laid out as a randomised block design. Inspections and plant counts were done every third day, when PEG-6000 additions were done, and emerged seeds were noted up until 14 days after planting, as in the emergence trial in chapter 3. This procedure was repeated three times for each seed lot to establish the mean emergence percentage for each seed lot.

Mean emergence percentage, mean emergence time and emergence index was calculated making use of the same formulas as mentioned before.

After statistical analysis all the cultivars were assigned a ranking from 1 to 14 according to mean emergence percentage, MET and EI.

4.2.4 Overall comparison

After statistical analysis all the cultivars were ranked from 1 to 14 for each experiment according to the testing parameter. The ranking results for each parameter was combined in a table (Table 4.5) whereafter each cultivar received a final overall ranking based on the average of the rankings from all the parameters.

The ranking results represent a vigour ranking, which in turn represents the expected field performance potential of each cultivar compared to the other tested cultivars.

4.2.5 Statistical analysis

Statistical analysis was performed by means of STATISTICA version 13.6.0 (TIBCO 2019). All the data was subjected to analysis of variance (ANOVA) to determine if there were any differences between cultivars, cultivar treatments and cultivar performance.

The data from the AA germination experiment and the corresponding MGT and GI results all followed a completely randomised design (CRD) with two treatment factors, including cultivar and aged time, and were all analysed by making use of a two-way ANOVA analysis.

Data from the AA emergence trial and the corresponding MGT and GI results all followed a randomised block design with two treatment factors, including cultivar and aged time, and a blocking factor. The data was analysed by making use of a two-way factorial ANOVA analysis with a blocking factor.

Data from the Planting depth trial and the corresponding MGT and GI results also followed a randomised block design with two treatment factors, including cultivar and planting depth, and a blocking factor. The data was also analysed by making use of a two-way factorial ANOVA analysis with a blocking factor.

Data from the drought stress trial followed a randomised block design, but with only one treatment factor, namely cultivar. The data therefore underwent a two-way ANOVA analysis to determine mean emergence differences between cultivars.

Fisher's least significant differences (LSD) test was conducted at a 5% significance level to determine whether differences within treatments and interactions between treatments were significant.

4.3 Results

4.3.1 Accelerated Ageing

4.3.1.1 Accelerated ageing germination

When comparing mean germination percentages of the different cultivars tested, in terms of their ageing times (0, 24, 48 and 72 hours), several differences were recorded within these different ageing treatments. Cultivars are represented in three groups, representing their herbicide resistance traits (Table 4.1). Germination percentages are represented in the four ageing classes per cultivar and statistically analysed per ageing class (Table 4.1). The mean MGT and GI results, over all aged treatments, was used as a mean simulation of cultivar germination and emergence performance over all treatments.

The mean germination results for each aged treatment are described below by dividing results into three categories, high, medium and low performing categories. Cultivars from different categories do not necessarily differ significantly ($p<0.05$), which can be seen in Table 4.1.

The AA germination results for the 0 hours aged treatment was similar to the standard germination results in Chapter 3. Cultivars 1, 2, 5, 6, 7, 10, 11, 12 and 13 all had mean germination percentages above 90%, making them the cultivars with the highest mean germination percentages. Cultivars 3, 4 and 9 are the three cultivars that had the second highest performance with regards to mean germination percentage, ranging between 70% and 81%. The two cultivars that showed the lowest performance were Cultivars 8 and 14, with mean germination percentages ranging between 30% and 40%. The performance of the last two categories mentioned was below the minimum 90% germination percentage as displayed on the product labels of these two cultivars.

The germination results for the 24 hours ageing treatment showed that Cultivars 5, 6, 7, 10, 11, 12 and 13 were the cultivars with the highest mean germination percentages, all still above 90%. Cultivars 1 and 2 showed a decrease in mean germination and went down a category and together with Cultivars 3, 4 and 9 were included within the second highest performance category, ranging between 65% and 81%. Cultivars 8 and 14 still showed the lowest mean germination percentages, 6.00% and 7.67% respectively, for the 24 hours aged treatment making them the two cultivars in the low performance category.

After 48 hours of ageing several cultivars started to show rapid decreases in germination performance. Cultivars 7 and 12 were the cultivars that still had the highest mean germination percentages, with 89.25% and 88.00% respectively. Cultivars 5, 10 and 13 were the cultivars that showed the second highest mean germination (medium-high), ranging between 60% and 80%. For the 48 hours ageing another medium category (medium-low) was created, showing that Cultivars 2, 6 and 11 had the third highest germination percentages, ranging between 15% and 40%. Cultivars 1, 3, 4, 8, 9 and 14 had the lowest mean germination percentages after 48 hours of ageing, with germination percentages ranging between 0% and 10%.

After 72 hours of ageing almost all the cultivars were non-viable, showing mean germination percentages of 0%. Only Cultivars 7, 10 and 12 still had a couple of seeds germinating after 72 hours of ageing, with mean germination percentages of 8.50%, 10.75% and 5.00% respectively. All the other tested cultivars showed mean germination percentages of 0%.

In terms of the mean MGT values the lowest performing category revealed MGT values of 6 days and above. The cultivars that resorted under this category included Cultivars 2, 3, 4, 5, 8, 9 and 14. The cultivars within the second-best performing category were Cultivars 1, 6, 11 and 13, which showed values between 5 days and 6 days. Cultivars with MGT values below 5 days were considered the best performing cultivars and included Cultivars 7, 10 and 12.

When considering the mean GI values for all the tested cultivars over all aged treatments, Cultivars 8 and 14 showed the lowest values, 1.83 and 1.71 respectively, and therefore had the lowest performance with regards to GI. Within the second highest performing category were Cultivars 1, 2, 3, 4 and 9 which showed GI values ranging between 2.00 and 10.00. Cultivars 5, 6, 7, 10, 11, 12 and 13 were the cultivars in the highest performing category and all had values ranging between 10.00 and 20.00.

All the cultivars showed fairly consistent rankings throughout all three parameters, with some bigger variations for Cultivars 5 and 6 at the MGT parameter.

Table 4.1: All germination parameters used for assessing 14 canola cultivars of South Africa for the year 2020 after accelerated ageing (AA) was applied. Values in brackets show the ranking given to each cultivar according to their column parameter (1= best and 14= worst). Rankings for mean germination percentage was calculated by adding the mean germination percentages for the four aged time sub-treatments. Cells with green and red shading indicate the highest and lowest performing values per column, respectively

Cultivar no.	Aged time (hours)					Overall mean germination time (days)	Overall germination index
	0	24	48	72	Ranking		
Conventional Cultivars	*Mean germination percentage (%)*						
6	99.25^{a}	90.25^{ab}	18.50^{e}	0.00^{c}	{8}	5.35^{g} {4}	13.58^{d} {6}
8	38.75^{c}	6.00^{e}	0.00^{f}	0.00^{c}	{13}	6.74^{a} {13}	1.83^{g} {13}
13	90.75^{a}	95.25^{a}	60.00^{c}	0.00^{c}	{5}	5.67^{ef} {6}	13.68^{d} {5}
14	35.00^{c}	7.67^{e}	0.00^{f}	0.00^{c}	{14}	6.77^{a} {14}	1.71^{g} {14}
Clearfield (CL) Cultivars							
1	92.00^{a}	72.75^{cd}	7.25^{ef}	0.00^{c}	{9}	5.92^{de} {7}	9.52^{e} {9}
2	94.75^{a}	81.00^{bc}	35.75^{d}	0.00^{c}	{7}	6.15^{bcd} {9}	9.72^{e} {8}
3	71.25^{b}	69.00^{d}	0.00^{f}	0.00^{c}	{12}	6.00^{cd} {8}	7.74^{f} {10}
4	80.25^{b}	65.75^{d}	8.50^{ef}	0.00^{c}	{10}	6.29^{bc} {10}	7.38^{f} {11}
Triazine Tolerant (TT) Cultivars							
5	98.25^{a}	90.25^{ab}	76.00^{b}	0.00^{c}	{4}	6.33^{b} {12}	15.26^{c} {4}
7	100.00^{a}	95.75^{a}	89.25^{a}	8.50^{ab}	{1}	4.70^{h} {1}	19.59^{a} {1}
9	71.50^{b}	75.00^{cd}	0.00^{f}	0.00^{c}	{11}	6.31^{b} {11}	7.14^{f} {12}
10	99.50^{a}	95.25a	60.00^{c}	10.75^{a}	{3}	4.91^{h} {3}	17.72^{b} {3}
11	98.00^{a}	96.50^{a}	37.25^{d}	0.00^{c}	{6}	5.56^{fg} {5}	13.08^{d} {7}
12	99.75^{a}	98.50^{a}	88.00^{a}	5.00^{b}	{2}	4.80^{h} {2}	19.45^{a} {2}

*Distinct letters above values within a column indicate significant ($p<0.05$) differences

4.3.1.2 Accelerated ageing emergence

Several statistical differences were recorded between the mean emergence percentage for each cultivar with regards to each ageing treatment (0, 24, 48 and 72 hours). Cultivars are represented in three groups, representing their herbicide resistance traits (Table 4.2). Mean emergence percentages are represented in the four ageing classes per cultivar and statistically analysed per ageing class (Table 4.2). The mean MET and EI results, over all aged treatments, was used as a mean simulation of cultivar performance over all treatments.

The mean emergence results for each aged treatment are described below by dividing results in three categories, high, medium and low performing categories. Cultivars from different categories do not necessarily differ significantly ($p<0.05$), which can be seen in Table 4.2.

The AA emergence results for the 0 hours aged treatment was similar to the glasshouse emergence trial reported in Chapter 3. For the 0 hours ageing treatment, Cultivars 1, 2, 5, 6, 7, 10, 11, 12 and 13 were all ranked in the highest performing category, with mean emergence percentages that ranged between 80% and 100%. The mean emergence percentages of Cultivars 3 and 9 were the second highest, ranging between 70% and 80%. Cultivars 4, 8 and 14 showed the lowest mean emergence percentages of all the cultivars with emergence values ranging between 30% and 60%

The emergence percentages of the same cultivars aged for 24 hours showed that Cultivars 2, 5, 6, 7, 10, 12 and 13 still achieved emergence percentages above 70% and were categorised as the highest performing cultivars after 24 hours of ageing. Cultivars 1, 3 and 11 had the second-best mean emergence percentages (medium-high), ranging between 50% and 70%. A second lowest category (medium-low) was also used to describe Cultivars 4 and 9, with values between 40% and 50%. Cultivars 8 and 14 still showed the lowest mean emergence percentages after 24 hours of ageing, 3.33% and 20.00% respectively.

After 48 hours of ageing several cultivars showed a severe drop in emergence percentages. Cultivars 1, 3, 4, 6, 8, 9 and 14 dropped to the lowest category with the lowest emergence percentages ranging between 0.00% and 7.00%. Cultivars 5, 7, 12 and 13 showed the highest mean emergence percentages after 48 hours of ageing, still performing relatively well with values between 50.00% and 70.00%. Cultivars 2, 10 and 11 showed emergence percentages between 30.00% and 40.00%, making them the second highest performing cultivars after 48 hours of ageing.

After 72 hours of ageing all the cultivars were non-viable and emergence percentages reported 0.00% emergence for all the tested cultivars, therefore no differences were recorded between the cultivars after 72 hours of ageing.

The mean MET values of all the cultivars, over all the aged treatments, is an indication of the average emergence performance of the cultivars after ageing. Cultivars 2, 7, 12 and 13 had the lowest MET values of all cultivars, below 10 days, and had the fastest emergence over all the ageing treatments overall. Cultivars 1, 3, 4, 5, 6, 9, 10 and 11 were the second-best performing cultivars ranging between 10 days and 12 days. The two cultivars categorised within the lowest performing category in terms of MET were Cultivars 8 and 14, with values above 13 days.

The mean emergence index (EI) results showed very similar results to the MET results, with Cultivars 7, 12 and 13 performing the best with the highest GI values, all above 8.0. Cultivars 8 and 14 had the lowest GI values indicating the lowest performance values, below 2.0. All the other cultivars ranged between the highest and lowest cultivars, similar to MET results.

All the cultivars showed fairly consistent rankings throughout all three parameters, with some slight differences occasionally.

Table 4.2: All emergence parameters used for assessing 14 canola cultivars of South Africa for the year 2020 after accelerated ageing (AA) was applied. Values in brackets show the ranking given to each cultivar according to their column parameter (1= best and 14= worst). Ranking for mean emergence percentage was calculated by adding the mean emergence percentages for the four aged time sub-treatments. Cells with green and red shading indicate the highest and lowest performing values per column, respectively

Cultivar no.	Aged time (hours)					Overall mean emergence time (days)	Overall emergence index
	0	24	48	72	Ranking		
Conventional Cultivars	*Mean emergence percentage (%)*						
6	86.67^{abc}	73.33^{abc}	6.67^{d}	0.00^{a}	{8}	10.64^{de} {6}	5.65^{cd} {8}
8	36.67^{d}	3.33^{f}	0.00^{d}	0.00^{a}	{14}	13.28^{a} {14}	0.93^{h} {14}
13	96.67^{ab}	80.00^{abc}	70.00^{a}	0.00^{a}	{1}	9.84^{f} {3}	8.22^{a} {3}
14	53.33^{d}	20.00^{f}	0.00^{d}	0.00^{a}	{13}	13.21^{a} {13}	1.59^{h} {13}
Clearfield (CL) Cultivars							
1	83.33^{abc}	63.33^{bcd}	3.33d	0.00^{a}	{9}	11.04^{cd} {9}	5.19^{de} {9}
2	93.33^{abc}	80.00^{abc}	36.67^{bc}	0.00^{a}	{5}	9.97^{ef} {4}	7.02^{b} {4}
3	76.67^{c}	56.67^{cd}	3.33^{d}	0.00^{a}	{10}	11.36^{bc} {11}	4.23^{ef} {10}
4	46.67^{d}	43.33^{de}	6.67^{d}	0.00^{a}	{12}	11.09^{cd} {10}	2.85^{g} {12}
Triazine Tolerant (TT) Cultivars							
5	100.00^{a}	73.33^{abc}	53.33^{ab}	0.00^{a}	{4}	10.70^{cd} {7}	6.40^{bc} {5}
7	96.67^{ab}	83.33^{ab}	63.33^{a}	0.00^{a}	{2}	9.02^{g} {1}	9.02^{a} {1}
9	76.67^{c}	40.00de	3.33^{d}	0.00^{a}	{11}	11.79^{b} {12}	3.29^{fg} {11}
10	80.00^{bc}	83.33^{ab}	30.00^{c}	0.00^{a}	{6}	10.75^{cd} {8}	5.79^{cd} {7}
11	90.00^{abc}	60.00^{bcd}	33.33^{bc}	0.00^{a}	{7}	10.60^{de} {5}	6.00^{bcd} {6}
12	93.33^{abc}	90.00^{a}	50.00^{abc}	0.00^{a}	{3}	9.47^{fg} {2}	8.55^{a} {2}

*Distinct letters above values within a column indicate significant ($p<0.05$) differences

4.3.2 Planting depth

Several differences were recorded when comparing different planting depth emergence results of the different cultivars tested. Cultivars are represented in three groups, representing their herbicide resistance traits. Mean emergence percentages are represented in the four planting depths per cultivar and statistically analysed per planting depth (Table 4.3). The mean MET and EI, for all planting depths, was used as a mean simulation of cultivar performance over all planting depths, in Table 4.3.

The mean emergence results for each planting depth treatment is described below by dividing results in three categories, high, medium and low performing categories. Cultivars from different categories do not necessarily differ significantly ($p<0.05$), which can be seen in Table 4.3.

At the 10 mm planting depth the mean emergence of Cultivars 2, 5, 7, 10, 11, 12 and 13 were l the highest with values ranging between 80.00% and 100.00 %. Cultivars 1, 4, 6 and 9 had lower mean emergence results compared to the highest performing cultivars and are therefore in the second-best category, with values ranging between 70.00% and 80.00%. The lowest performing cultivars at the 10 mm planting depth were Cultivars 3, 8 and 14, with values of 50.00%, 56.67% and 66.67% respectively.

At the 20 mm planting depth Cultivars 1, 2, 5, 6, 7, 10, 11, 12 and 13 were the cultivars with the highest mean emergence percentages, ranging between 70.00% and 100.00%. Cultivars 3, 4 and 9 were the second-best performing cultivars, with values ranging between 60.00% and 70.00%. The two cultivars with the lowest emergence percentages at a planting depth of 20 mm, namely Cultivars 8 and 14 both showed only 40.00% mean emergence.

Cultivars 7, 10 and 12 were the cultivars with the highest emergence percentages at a planting depth of 40 mm, ranging between 60.00% and 80.00%. The second highest performing cultivars include Cultivars 1, 2, 3, 4, 5, 6, 9 and 11 and had mean emergence values ranging from 40.00% to 60.00%. Cultivars 8, 13 and 14 were the lowest performing cultivars at a planting depth of 40 mm, with mean emergence values below 40.00%.

At a planting depth of 60 mm the overall emergence percentage of all cultivars declined markedly. Although the emergence values are lower, Cultivars 1, 6, 7 and 10 were still the best performing cultivars with mean emergence values between 20.00% and 50.00%. For the mean emergence percentages at the planting depth of 60 mm no medium performance category was identified with all the other cultivars classified together as having the lowest performance, with emergence percentages ranging between 0.00% and 20.00%.

The mean MET is an indication of the average emergence performance of all the tested cultivars over all the tested planting depths. Cultivars 8 and 14 emerged at the slowest rate and had the highest MET values for the planting depth trial, at 15.64 days and 16.52 days, respectively. Cultivars 6, 7, 10, 11, 12 and 13 had the lowest MET values of all cultivars, (below 10 days), and overall had the fastest emergence over all the planting depths. Cultivars 1, 2, 3, 4, 5 and 9 were the second-best performing cultivars ranging between 10 days and 13 days.

Cultivar 7 had the highest overall EI value ($p<0.05$) for all planting depths and is considered the cultivar with the best emergence rate. Cultivars 8 and 14 were the cultivars with the lowest emergence rate with EI values of 2.25 and 2.29, respectively. All the other cultivars had EI values ranging between 5 and 10 and were considered the second-best performing cultivars.

All the cultivars showed fairly consistent rankings over all three parameters, with occasional slight differences. Cultivars 5 and 11 showed the largest differences between rankings, with Cultivar 5 showing a lower mean emergence ranking than MET and EI rankings. Cultivar 11, conversely, had a higher-ranking value for mean emergence compared to the MET and EI rankings.

Table 4.3: All emergence parameters used for assessing 14 canola cultivars of South Africa for the year 2020 at different planting depths. Values in brackets show the ranking given to each cultivar according to their column parameter (1= best and 14= worst). Ranking for mean emergence percentage was calculated by adding the mean emergence percentages for the four planting depth sub-treatments. Cells with green and red shading indicate the highest and lowest performing values per column, respectively

Cultivar no.	Planting depth (mm)					Overall mean emergence time (days)	Overall emergence index
	10	20	40	60	Ranking		
Conventional Cultivars	*Mean emergence percentage (%)*						
6	76.67^{cd}	93.33^{a}	53.33^{abc}	23.33^{abcd}	{5}	9.49^{c} {5}	9.54^{b} {3}
8	56.67^{e}	40.00^{c}	13.33^{e}	10.00^{cd}	{13}	15.64^{a} {13}	2.25^{f} {13}
13	96.67^{ab}	96.67^{a}	33.33^{cde}	6.67^{cd}	{8}	9.83^{c} {6}	9.04^{bc} {7}
14	50.00^{e}	40.00^{c}	23.33^{de}	0.00^{d}	{14}	16.52^{a} {14}	2.29^{f} {14}
Clearfield (CL) Cultivars							
1	76.67^{cd}	73.33^{ab}	46.67^{bcd}	26.67^{abc}	{9}	10.22^{bc} {7}	7.82^{cd} {9}
2	93.33^{abc}	83.33^{ab}	50.00^{bc}	6.67^{cd}	{8}	10.30^{bc} {8}	9.14^{bc} {6}
3	66.67^{de}	66.67^{b}	46.67^{bcd}	13.33^{bcd}	{12}	11.11^{bc} {11}	5.79^{e} {11}
4	76.67^{cd}	66.67^{b}	56.67^{dbc}	6.67^{cd}	{10}	10.85^{bc} {10}	6.18^{de} {10}
Triazine Tolerant (TT) Cultivars							
5	100.00^{a}	93.33^{a}	46.67^{bcd}	6.67^{cd}	{4}	10.56^{bc} {9}	8.83^{bc} {8}
7	93.33^{abc}	93.33^{a}	76.67^{a}	36.67^{ab}	{1}	8.87^{c} {1}	12.03^{a} {1}
9	76.67^{cd}	66.67^{b}	50.00^{bc}	6.67^{cd}	{11}	12.34^{b} {12}	5.55^{e} {12}
10	83.33^{abcd}	73.33^{ab}	66.67^{ab}	43.33^{a}	{2}	9.43^{c} {3}	9.15^{bc} {5}
11	83.33^{abcd}	93.33^{a}	43.33^{bcd}	16.67^{bcd}	{6}	8.97^{c} {2}	9.77^{b} {2}
12	80.00^{bcd}	90.00^{ab}	66.67^{ab}	10.00^{cd}	{3}	9.46^{c} {4}	9.45^{bc} {4}

*Distinct letters above values within a column indicate significant ($p<0.05$) difference

4.3.3 Drought stress

Several statistical differences were recorded between the different commonly cultivated canola cultivars tested with regards to their mean emergence percentages under drought stress conditions. Cultivars are represented in three groups, representing their herbicide resistance traits (Table 4.4).

The mean emergence results for each cultivar in the drought stress trial is described below by dividing results in three categories, high, medium and low performing categories. Cultivars from different categories do not necessarily differ significantly ($p<0.05$), which can be seen in Table 4.4.

Cultivars 5, 6, 7 and 13 had the highest mean emergence percentages under drought stress conditions, ranging between 60.00% and 75.00%. Cultivars 8 and 14 showed the lowest mean emergence percentages of all the cultivars in the drought stress trial, with mean emergence values of 0.00% and 10.00% respectively. All the other cultivars emergence percentages were scattered between 20.00% and 60.00% and were the second highest performing cultivars with regards to drought stress resistance.

Cultivars 3, 5, 8, 9, 10 and 14 all emerged at the slowest rate, ranging between 12.00 days and 14.00 days. Cultivars 1, 2, 4, 11, 12 and 13 were the cultivars with the second highest MET values ranging between 10.00 days and 12.00 days. The best performing cultivars, with regards to MET, which recorded values ranging between 9.00 days and 10.00 days, were Cultivars 6 and 7.

Cultivars 6, 7 and 13 had the highest EI values for the drought stress trial, with EI values above 6.5. Cultivars 1, 2, 3, 4, 5, 9, 10, 11 and 12 were the cultivars which achieved the second highest EI values, ranging between 2.0 and 6.5. Cultivars 8 and 14 were the two cultivars with the lowest EI values and therefore had the worst emergence rate, with values below 1.0.

All the cultivars showed rather consistent rankings throughout all three parameters, with some bigger differences for Cultivars 1, 5, 12 and 13 at the MET parameter. Cultivars 5 and 13 had higher MET ranking values compared to the other tested parameters, whereas Cultivars 1 and 12 showed lower MET ranking values.

Table 4.4: All emergence parameters used for assessing 14 canola cultivars of South Africa for the year 2020 with regards to drought stress resistance. Values in brackets show the ranking given to each cultivar according to their column parameter (1= best and 14= worst). Cells with green and red shading indicate the highest and lowest performing values per column, respectively

Cultivar no.	**Mean emergence percentage**	**MET**	**EI**
Conventional Cultivars	*(%)*	*(days)*	
6	63.33^{abc} {3}	9.80^{d} {2}	6.75^{ab} {2}
8	10.00^{fg} {13}	13.33^{ab} {12}	0.75^{ef} {13}
13	73.33^{a} {1}	11.44^{bcd} {6}	7.46^{a} {1}
14	0.00^{f} {14}	14.00^{a} {14}	0.00^{f} {14}
Clearfield (CL) Cultivars			
1	26.67^{ef} {11}	11.92^{bc} {7}	2.28^{de} {11}
2	53.33^{abcd} {5}	11.27^{cd} {5}	4.95^{bc} {6}
3	26.67^{ef} {12}	13.40^{ab} {13}	2.12^{def} {12}
4	43.33^{cde} {7}	11.97^{bc} {8}	3.78^{cd} {8}
Triazine Tolerant (TT) Cultivars			
5	66.67^{ab} {2}	12.37^{abc} {10}	5.45^{abc} {4}
7	60.00^{abc} {4}	9.65^{d} {1}	6.57^{ab} {3}
9	43.33^{cde} {8}	12.22^{abc} {9}	3.58^{cd} {9}
10	36.67^{de} {10}	12.38^{abc} {11}	3.54^{cd} {10}
11	50.00^{bcd} {6}	11.13^{cd} {4}	5.25^{bc} {5}
12	46.67^{bcde} {9}	10.70^{cd} {3}	4.83^{bc} {7}

*Distinct letters above values within a column indicate significant ($p<0.05$) differences

4.3.4 Overall comparison

The results from all rankings (Table 4.5), as ranked after each vigour test, showed some interesting results. Cultivars 7, 12, 13 and 6, in ranking order from 1st to 4th, were ranked as the four best performing cultivars with regards to vigour testing overall.

Cultivars 8 and 14 were the two cultivars with the lowest overall ranking across all the tested vigour parameters. Since these two cultivars were ranked the lowest, it is believed that they have the lowest field performance potential.

Within the overall rankings (Table 4.5), there is some variation for some cultivars between testing parameters. Cultivars 4, 5, 6 and 9 showed to have better rankings in drought stress testing compared to the other parameters. Cultivars 1, 7, 10 and 12 has lower rankings in drought stress testing compared to the other parameters. Cultivar 13 showed lots of variation across all the testing parameters.

Table 4.5: Overall ranking results as ranked after each seed vigour test used for assessing 14 canola cultivars of South Africa for the year 2020

Cultivar no.	AA germination	AA germination - MGT	AA germination - GI	AA emergence	AA emergence - MET	AA emergence - EI	Planting depth	Planting depth - EI	Planting depth - MET	Drought stress	Drought stress - MET	Drought stress - EI	Average Ranking Value	Overall Ranking
Conventional Cultivars														
6	8	4	6	8	6	8	5	5	3	3	2	2	5	**4**
8	13	13	13	14	14	14	13	13	13	13	12	13	13.2	**13**
13	5	6	5	1	3	3	8	6	7	1	6	1	4.3	**3**
14	14	14	14	13	13	13	14	14	14	14	14	14	13.8	**14**
Clearfield (CL) Cultivars														
1	9	7	9	9	9	9	9	7	9	11	7	11	8.8	**9**
2	7	9	8	5	4	4	7	8	6	5	5	6	6.2	**8**
3	12	8	10	10	11	10	12	11	11	12	13	12	11	**12**
4	10	10	11	12	10	12	10	10	10	7	8	8	9.8	**10**
Triazine Tolerant (TT) Cultivars														
5	4	12	4	4	7	5	4	9	8	2	10	4	6.1	**7**
7	1	1	1	2	1	1	1	1	1	4	1	3	1.5	**1**
9	11	11	12	11	12	11	11	12	12	8	9	9	10.8	**11**
10	3	3	3	6	8	7	2	3	5	10	11	10	5.9	**6**
11	6	5	7	7	5	6	6	2	2	6	4	5	5.1	**5**
12	2	2	2	3	2	2	3	4	4	9	3	7	3.6	**2**

4.4 Discussion

4.4.1 Accelerated Ageing (AA)

4.4.1.1 Accelerated ageing germination

The AA test is designed to expose seeds to aggressive ageing conditions, through humidity and heat, in a climate-controlled chamber, to induce seed deterioration (Marcos-Filho 2015). Seed lots with a high vigour should be able to withstand these extreme ageing conditions and therefore deteriorate at a slower rate compared to seed lots with low vigour (Hampton and Tekrony 1995). After seed ageing, seeds were evaluated to determine the new mean germination percentage after the specific ageing treatment. The closer the post-ageing germination percentages are to the pre-ageing germination percentage, after 0 hours of ageing, the higher the specific seed lot's vigour is considered to be (Elliott et al. 2007).

In Table 4.1 Cultivars 7, 10 and 12 were the cultivars that showed the highest performance with regards to germination after the AA procedure and most probably have the highest seed vigour and field performance potential, according to (Elliott et al. 2007). These three cultivars also had the best results with regards to MGT and GI, and therefore shows a good germination rate which is a good indication of high seed vigour (Moradi Dezfuli et al. 2008).

Cultivars 8 and 14 showed the lowest performance overall with regards to the germination results after accelerated ageing. Both of these cultivars started off with very low germination percentages, which is already an indication that seed deterioration has begun and seed vigour is low (Hampton and Coolbear 1990).

The performance of Cultivars 3 and 9 have also given some cause for concern, although their results are not as low as those of Cultivars 8 and 14. Results from these two cultivars suggest that seed deterioration had already begun and that the seed vigour and field performance potential is lower than the other cultivars, except Cultivars 8 and 14.

All the other cultivars had varying results but were all within a satisfactory margin compared to the lowest performing cultivars. These cultivars are believed to have good seed vigour and field performance potential.

4.4.1.2 Accelerated ageing emergence

According to Finch-Savage and Bassel (2015), seed emergence is one of the most important factors in crop production and results in a good field establishment. Therefore, seed quality needs to be optimal to ensure optimal field emergence and crop performance. Seed lots with a high vigour should be able to withstand extreme ageing conditions and therefore deteriorate at a slower rate compared to seed lots with low vigour (Hampton and Tekrony 1995). Therefore, seed lots with a high seed vigour should still show good emergence percentages, even after ageing.

The cultivars performing best overall in this trial appear to be Cultivars 7, 12 and 13. These cultivars had the least variation between mean emergence results for all the ageing treatments and showed the best mean emergence results. The MET and EI results for these three cultivars were also the best compared to the other cultivars tested. These cultivars are believed to have good seed vigour and have a high field performance potential (Hampton and Tekrony 1995; Elliott et al. 2007; ISTA 2020).

Cultivars 4, 8 and 14 were the cultivars that had the lowest performance with regards to mean emergence after ageing (Table 4.2). Cultivars 4 and 14 are ranked in the lower range of results and are believed to have a low seed vigour and performance potential but are still ranked higher than Cultivar 8. Cultivar 8 showed the lowest emergence potential, MET and EI of all the tested cultivars and, according to Hampton and Tekrony (1995) and Elliott et al. (2007), has low seed vigour and field performance potential.

All the other cultivars had varying results but are all within a satisfactory margin compared to the lowest performing cultivars. These cultivars are believed to have good seed vigour and field performance potential (Finch-Savage and Bassel 2015).

Cultivar 14 reported a lower mean germination percentage (Table 4.1) compared to mean emergence percentage (Table 4.2). In Table 4.1, Cultivar 14 had a very slow germination rate and might not have reached its peak of germination when the final evaluation was done. Since ISTA (2020) stated that the final count should be done at 7 days and also for consistency across the experiment, the experiment time for Cultivar 14 was not extended. Due to these facts, it is believed that Cultivar 14 might have had a somewhat higher mean germination percentage and therefore possibly explaining the difference between mean germination percentage and mean emergence percentage. The very slow rate of germination is however still a concerning indication of possible low seed vigour for this cultivar.

Cultivars 3, 5, 9 and 13 also showed a marginally higher mean emergence percentage compared to mean germination percentage. This variation can be explained by the random nature of the experiment, where different randomly selected seed is tested for each experiment and natural variation in a seed lot could have played a role.

4.4.2 Planting depth

Seed emergence and crop establishment is one of the most important factors in crop production systems and has a determining effect on the total yield, therefore seeds need to emerge as uniformly and abundantly as possible (Finch-Savage and Bassel 2015). Seeds with higher vigour will emerge better even from deeper planting depths, therefore emergence and emergence rate can give good indication of the seed vigour of a seed lot (Larsen 1964; de Oliveira et al. 2019).

Cultivars 7, 10 and 12 were the cultivars that performed the best overall, showing the best mean emergence percentages, MET and EI at all planting depths (Table 4.3).

Cultivars 8 and 14 had the lowest performance across all planting depths and for all the emergence parameters. This low performance suggests that these cultivars have low seed vigour and field performance potential, according to Hampton and Tekrony (1995) and Elliott et al. (2007).

Although Cultivars 3, 4 and 9 did not have the lowest performance, the results reported for these three cultivars were considerably lower than the remainder of the tested cultivars. These cultivars should still perform relatively well, but the field performance potential and seed vigour are considered lower than for the other cultivars, with the obvious exception of Cultivars 8 and 14.

All the other cultivars had varying results but are all within a satisfactory margin compared to the lowest performing cultivars. These cultivars are believed to have good seed vigour and field performance potential (Finch-Savage and Bassel 2015; de Oliveira et al. 2019).

4.4.3 Drought stress

Pantola et al. (2017) showed that increasing drought stress negatively impacts seed germination and therefore emergence. Although crop genetics has the biggest effect on drought tolerance, increasing seed vigour also showed better emergence under drier conditions (Pantola et al. 2017). Chloupek et al. (2003) also made use of drought stress as an indication of seed vigour and better resistance indicated a higher seed vigour and performance potential.

In the results reported in Table 4.4, it is clear that Cultivars 5, 6, 7 and 13 had the highest mean emergence percentages (>60%) under drought conditions and also gave the best overall performance when taking all the emergence parameters into account. All these cultivars are believed to have good seed vigour and field performance potential. Although Cultivar 13 showed a rather high MET value (11.44 days), comparing all the parameters, including mean emergence percentage and EI, it appeared to be the best performing cultivar out of all those tested.

Cultivars 8 and 14 were the cultivars with the lowest performance potential and seed vigour, as they showed the lowest mean emergence, MET and EI results out of all the tested cultivars.

Although the other cultivars showed lower mean emergence results, it does not directly represent their field performance potential. The drought test is used to determine separations in seed vigour and these cultivars still performed reasonably well under drought conditions (Chloupek et al. 2003; Pantola et al. 2017). It is therefore believed that these cultivars will deliver satisfactory field results, with minimum field emergence percentages above 50%, as stated by Harker et al. (2012) and the Protein Research Foundation (2018).

4.4.4 Overall comparison

Table 4.5 showed that after taking all the tested parameters results into consideration, Cultivars 6, 7, 12 and 13 showed the best overall rankings. Since these cultivars reported the best results over all the tested vigour parameters, it is believed that they possess the highest seed vigour and field performance potential compared to the other tested cultivars (Elliott et al. 2007; Finch-Savage and Bassel 2015; Pantola et al. 2017; de Oliveira et al. 2019).

Cultivars 8 and 14 were the two cultivars with the lowest overall ranking across all the tested vigour parameters. Since these two cultivars were ranked the lowest, it is believed that they have the lowest field performance potential (Heydecker 1972; Baalbaki et al. 2009).

Although Cultivars 3 and 9 did not show the lowest overall performance, they still showed low performance throughout all the vigour testing parameters. These results suggest that seed deterioration has already begun and that the seed vigour and field potential is lower than the other tested cultivars, except for Cultivars 8 and 14 (Hampton and Tekrony 1995).

Within the overall rankings some variation for certain cultivars, was noted between testing parameters. Some variation is expected between testing parameters, since each parameter tested seed vigour based on different stress bases. This is especially so with the drought stress parameter where genetic drought resistance also plays a major role. This variation can also possibly be intensified by the random nature of the experiment, where different randomly selected seed is tested for each experiment. The overall ranking is therefore used as a summary of the average results of the cultivar within all vigour testing parameters. The vigour testing parameters will be correlated to field performance in Chapter 5 to determine which one is considered the best.

4.5 Conclusion

In this study Cultivars 6, 7, 12 and 13 are considered the best performing cultivars, compared to other cultivars tested, over all the tested vigour parameters tested in this chapter. Although these cultivars did not significantly do the best in all the vigour testing parameters, on average across all testing they proved to be most promising. Cultivar 7 was the best performing cultivar and therefore has the highest seed vigour ranking. Since these cultivars have the highest seed vigour rankings, it is believed that they also have the highest overall field performance potential (Finch-Savage and Bassel 2015).

Overall Cultivars 8 and 14 showed the lowest performance throughout all the vigour testing parameters done in this study. Cultivar 3 raised some concern throughout vigour testing but did not perform as poorly as Cultivars 8 and 14. Therefore, it can be concluded in this chapter, that Cultivars 8 and 14 appear to have the lowest seed vigour and field performance potential and are expected to show unsatisfying overall field performance results. This statement will be investigated by means of field trials in Chapter 5.

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Chapter 5

Field performance of common South African canola cultivars

5.1 Introduction

Worldwide, canola (*Brassica napus* L.) is the third largest oilseed crop commercially produced, surpassed only by soyabeans and palm oil (Gunstone 2001; Wang et al. 2009). Canola's production hectares in the Western Cape of South Africa increased from around only 17 000 ha in the 1999 season to between 70 000 and 85 000 ha currently and has thus formed an integral part of the production systems of these areas (GrainSA 2020; Sihlobo 2018). The total production of canola in South Africa is however still generally lower than the demand indicating scope to increase production even more (PRF 2018).

To ensure optimal yields, seed emergence and crop establishment are among the most important factors with a determining effect on the total yield and therefore seeds need to emerge as uniformly and abundantly as possible (Finch-Savage and Bassel 2015). Certified seed quality in South Africa is generally demonstrated on product labels by means of germination percentage, which is a requirement by the South African National Seed Organization (SENSAKO 2019; SANSOR 2020). Most seed marketing companies will also add the thousand seed mass (TSM) or mass of some sort on product labels (SENSAKO 2019; SANSOR 2020).

Germination percentage as a seed quality indicator is not only used in South Africa, but is also the most common indicator of seed performance in the world (Hampton 2002). The minimum certification germination percentage for canola as stated in the plant improvement act of 1976 (ACT No. 53 OF 1976) of South Africa is 70% (Didiza 2002). Germination percentage shows a quality indication of seed germinating under optimal conditions in a laboratory, which is almost never the case in the field. Hampton (1993) stated that a seed vigour test should be able to provide a more sensitive index of seed quality compared to the standard germination test and should consistently rank seed lots in terms of potential field performance. Since the regular practice of seed vigour testing as a seed quality indicator has yet to become established in the South African seed industry, no comparison can be made between canola cultivars with regards to seed vigour and potential field performance (Van De Venter and Lock 2013).

The aim of this study is to determine the overall field performance, from establishment to yield, of 14 different commonly cultivated canola cultivars of South Africa for the year 2020. The results of the field trials will then be compared to general seed quality and seed vigour results from previous chapters to determine their correlations and relationship. This study only encompasses data for seed from the year 2020 to illustrate a one year 'snap-shot' of the quality of canola cultivar seed in South Africa and can vary from year to year.

5.2 Materials and methods

5.2.1 Trial sites

This field study was conducted on four sites in the canola production areas across the Western Cape of South Africa during the 2020 production season. Trial sites were scattered between the Southern Cape, Overberg and Swartland production regions. The selection of sites was based on variation in climate and soil conditions which tested the different canola cultivar's performance under various conditions.

The four main sites for the 2020 production season included a farm near Riversdale (Uitkyk – 34°06'52.9" S, 21°05'38.1" E), a farm near Riviersonderend (Tygerhoek Research Farm - 34°10'10.6" S, 19°54'57.8" E), a farm near Hopefield (Waterboerskraal – 33°02'17.0" S, 18°26'29.2" E) and a farm near Moorreesburg (Langgewens Research Farm - 33°16'50.9" S, 18°42'46.6" E), as indicated in Figure 5.1. The trail was repeated twice at Langgewens- and -Tygerhoek research farms with different planting dates to create even more variation in growing conditions.

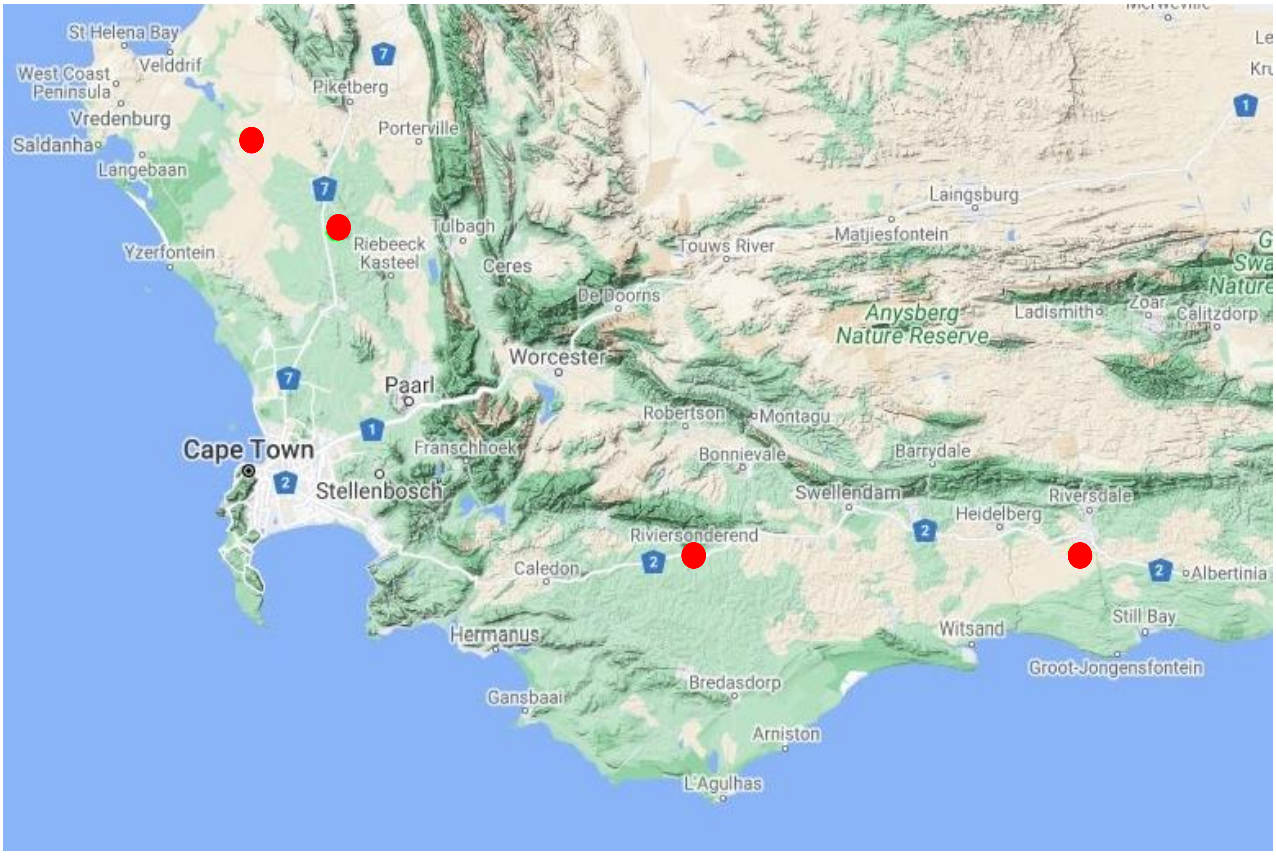

Figure 5.1: Trial sites, indicated by red dots, of canola cultivar trials for the 2020 production season indicated on a map of the Western Cape of South Africa.

5.2.2 Climate

All the trial sites are situated in areas which have a Mediterranean-type climate with the highest proportion of rainfall occurring in the months from April to October. The Swartland generally receives approximately 80 - 85% of its total yearly rainfall between these months and the Southern Cape and Overberg approximately 60 - 70% (FERTASA 2016).

5.2.2.1 Riversdale (Uitkyk)

The mean long-term rainfall for the Riversdale region, for the production season from April to October, is 291.2 mm per annum (Figure 5.2). The total rainfall within the 2020 production season was 21 mm lower than the long term mean, receiving 270.2 mm from April to October 2020 (Figure 5.2). April showed rainfall lower than the long term mean but May was slightly above the mean. Since crops were only planted in May at this site, sufficient moisture was available. June, July and August 2020 received rainfall amounts above the long term mean and September showed similar amounts to the long term mean. October was a dry month at this trial site, recording rainfall amounts significantly lower than the long-term mean. Considering the maximum temperature data for Riversdale it is clear that the 2020 season was fairly normal compared to the long term averages, except for August which was colder than the long term mean. April to July recorded minimum temperatures above the long-term average, but August to October was considered normal. Overall weather data showed cold to normal temperatures during the flowering and pod fill stages of canola production, which is very beneficial for optimum yield.

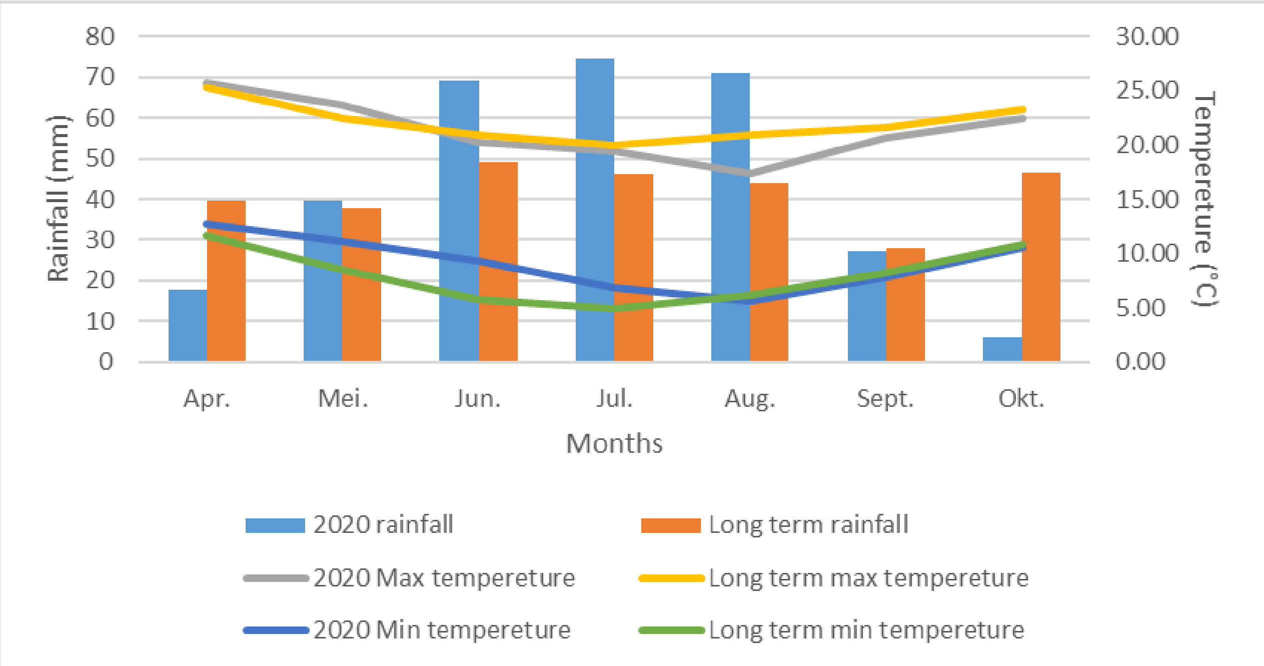

Figure 5.2: Monthly minimum-and-maximum temperatures and rainfall data for the 2020 production season compared to the long term mean monthly temperatures and rainfall at Uitkyk farm near Riversdale.

5.2.2.2 Riviersonderend (Tygerhoek research farm)

The mean rainfall over the past 70 years at Tygerhoek research farm, for the production season from April to October, is 286.4 mm per annum (Figure 5.3). The 2020 production season exceeded the long-term average rainfall, receiving 338.8 mm total rainfall from April to October 2020 (Figure 5.3). April and May had lower rainfall than the long-term means, which suggested that during planting slightly dry conditions were present. The rest of the months within the production year were mostly above the long-term averages. When considering the minimum and maximum temperatures for 2020 versus the long-term averages, 2022 was a fairly normal year with regard to temperatures. The month of August showed minimum and maximum temperatures to be slightly lower than the long-term averages, which is very beneficial for canola during its flowering stage.

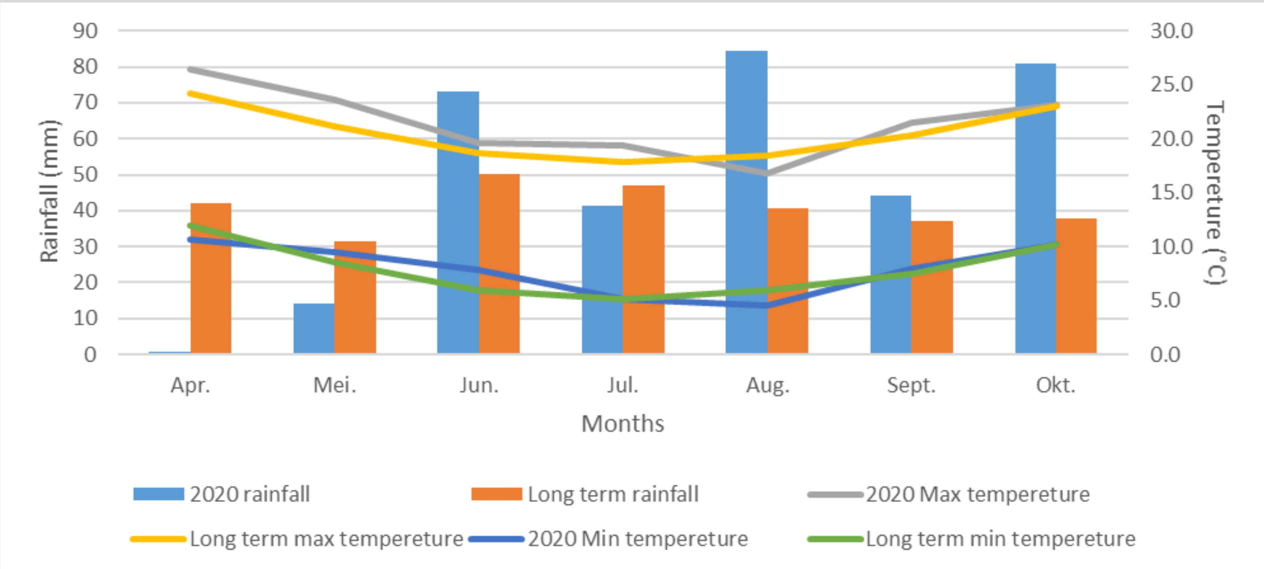

Figure 5.3: Monthly minimum-and-maximum temperatures and rainfall data for the 2020 production season compared to the long term mean monthly temperatures and rainfall at Tygerhoek research farm near Riviersonderend.

5.2.2.3 Hopefield (Waterboerskraal)

The mean long-term rainfall for the Hopefield region, for the production season from April to October, is 271.8 mm per annum (Figure 5.4). The total rainfall during the 2020 production season was very similar to the long-term mean, with this site receiving 272.2 mm from April to October 2020 (Figure 5.2). April recorded rainfall slightly higher than the long term mean and May was significantly lower than the mean. The low rainfall in May indicated dry conditions during planting and establishment for this trial site. June, July and August 2020 received rainfall amounts either similar to (June) or above the long-term mean (July and August). The end of the production season was slightly drier than the long-term mean, with September and October recording rainfall amounts lower than the long term means. Due to a faulty thermometer at the Hopefield trial site, only rainfall data will be shown for this study.

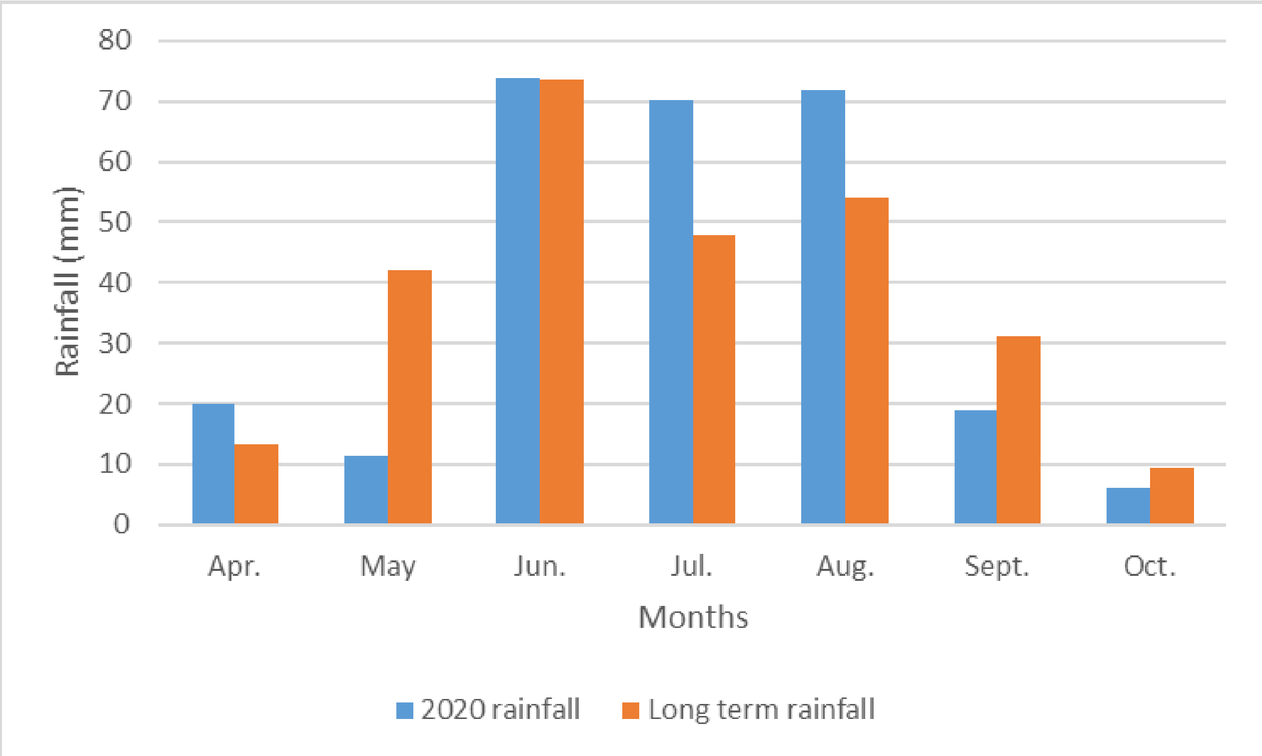

Figure 5.4: Monthly rainfall for the 2020 production year compared to the long term mean monthly rainfall at Waterboerskraal, a farm near Hopefield.

5.2.2.4 Moorreesburg (Langgewens research farm)

The mean rainfall over the past 70 years at Langgewens Research Farm for the production season from April to October, was 333.0 mm per annum (Figure 5.5). The 2020 production year's total rainfall was rather similar to the long-term mean, receiving 305.2 mm total rainfall from April to October 2020 (Figure 5.5). April and May showed rainfall lower than the long term mean, which suggested that during planting dry conditions were present. June, July and August 2020 received rainfall amounts above the long-term mean. The end of the production season was slightly drier than the long term means, with September and October also recording rainfall amounts lower than the long term means. When considering the minimum and maximum temperatures for 2020 versus the long-term means at Langgewens, overall a fairly normal year occurred with regard to temperatures. At Langgewens Research Farm the months of August and September showed minimum and maximum temperatures to be slightly lower than the long term averages, which is very beneficial for canola during the flowering stage.

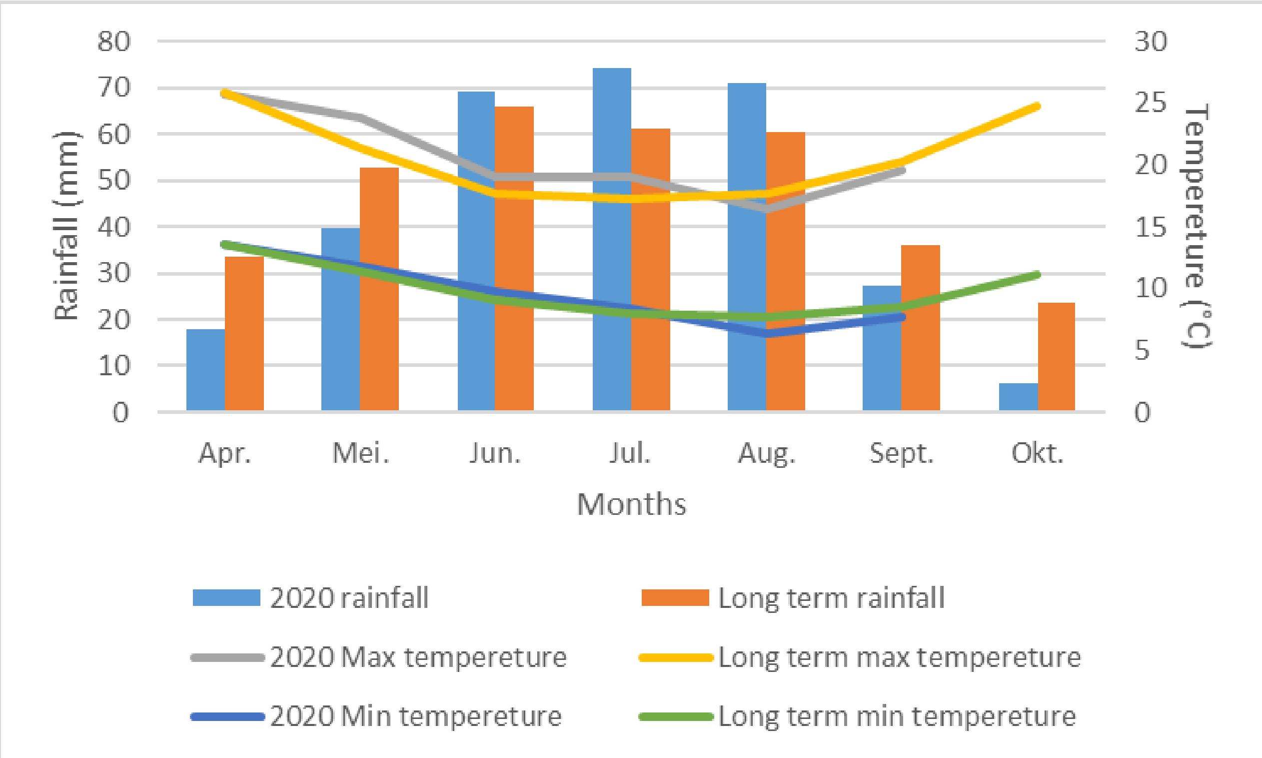

Figure 5.5: Monthly minimum-and-maximum temperatures and rainfall data for the 2020 production season compared to the long term mean monthly temperatures and rainfall at Langgewens research farm near Moorreesburg.

5.2.3 Soil

Soil samples taken prior to planting were used to determine the mean bulk densities and soil moisture content, in terms of percentage per volume, for all the trials. This data was collected to fully understand the soil physical properties and moisture conditions seeds were exposed to during establishment.

Soil sampling was done just before planting by taking ten random representative soil samples across the trial area. Samples were taken by means of a metal pipe (45 mm outside diameter and 43 mm inside diameter) at two depths, namely 0 mm - 150 mm and 150 mm – 300 mm. Soil samples were then immediately weighed before placing them in an oven, set at 105 °C, until a constant weight was attained, and all moisture removed. Samples were then weighed again, whereafter the mean bulk density and mean soil moisture content for each trial could be calculated.

The formula used for calculating the soil bulk density is as described by Hossain et al. (2015):

$$Soil\ Bulk\ Density\ (g\ cm^{-3}) = \frac{weight\ of\ dry\ soil\ (g)}{Volume\ of\ core\ (cm^3)}$$

and;

$$Volume\ of\ core\ (cm^3) = \pi \times r^2 \times h$$

where:

π = Pi = 3.1416;

r = radius of core;

h = height of core.

The formula used for calculating the volumetric soil moisture percentage is as described by the GRDC (2018a):

$$Moisture\ Contents\ (\%) = \frac{W_{WS} - W_{DS}}{W_{WS}} \times 100$$

where:

W_{WS} = Weight of soil sample before drying (wet sample);

W_{DS}= Weight of soil sample after drying (dry sample).

5.2.3.1 Riversdale (Uitkyk)

These soils are usually characterised by accumulation of clay, strongly structured and a non-reddish colour with a strong texture contrast (CapeFarmMapper 2020). These soils usually have depths of <450 mm and clay percentages of <15% (CapeFarmMapper 2020). This specific trial site has a large stone fraction.

The mean bulk density of the exact soil where the trial was laid out was 1.33 g cm^{-3}, for the 0 mm – 150 mm depth, and 1.66 g cm^{-3}, for the 150 mm – 300 mm depth. The mean volumetric soil moisture percentage of the soil was 6.55%, for the 0 mm – 150 mm depth, and 8.16%, for the 150 mm – 300 mm depth.

5.2.3.2 Riviersonderend (Tygerhoek research farm)

Soils from this area are also generally considered soils with a strong texture contrast. These soils are known for their accumulation of clay, strong structure and a non-reddish colour (CapeFarmMapper 2020). These soils usually have depths of between 450 mm and 750 mm and clay percentages of <15% (CapeFarmMapper 2020). The soils where this trial was laid out in fact have shallow soils of about 300 mm where a shale bank is present.

The trial was repeated twice at this site, at two different planting dates, and therefore two sets of bulk density and soil moisture samples were taken to establish the exact conditions for each trial at planting. The mean bulk density of the soil where the first trial was laid out was 1.18 g cm^{3}, for the 0 mm – 150 mm depth, and 1.65 g cm^{-3}, for the 150 mm – 300 mm depth. The mean volumetric soil moisture percentage was 10.9%, for the 0 mm – 150 mm depth, and 9.98%, for the 150 mm – 300 mm depth.

The mean bulk density of the soil area where the second trial was laid out, at planting, was 1.20 g cm^{-3}, for the 0 mm – 150 mm depth, and 1.62 g cm^{-3}, for the 150 mm – 300 mm depth. The mean volumetric soil moisture percentage was 8.48%, for the 0 mm – 150 mm depth, and 8.32%, for the 150 mm – 300 mm depth.

5.2.3.3 Hopefield (Waterboerskraal)

Soils from this area are generally described as soils with limited pedological development. Soils are characteristically sandy, greyish in colour and excessively drained (CapeFarmMapper 2020). These are usually deep soils, with depths of >750 mm and low clay percentages, <15% (CapeFarmMapper 2020).

The mean bulk density of the exact soil where the trial was laid out was 1.64 g cm^{-3}, for the 0 mm – 150 mm depth, and 1.79 g cm^{-3}, for the 150 mm – 300 mm depth. The mean volumetric soil moisture percentage of the soil was 1.22%, for the 0 mm – 150 mm depth, and 1.28%, for the 150 mm – 300 mm depth.

5.2.3.4 Moorreesburg (Langgewens research farm)

Soils from this area are generally soils with a strong texture contrast. These soils are known to be strongly structured with accumulation of clay and a reddish colour (CapeFarmMapper 2020). These soils usually have depths of between 450 mm and 750 mm and clay percentages of between 15% and 35% (CapeFarmMapper 2020).

The trial was repeated twice at this site, at two different planting dates, and therefore two sets of bulk density and soil moisture samples were taken to establish the exact conditions for each trial at planting. The mean bulk density of the soil where the first trial was laid out was 1.41 g cm^{3}, for the 0 mm – 150 mm depth, and 1.78 g cm^{-3}, for the 150 mm – 300 mm depth. The mean volumetric soil moisture percentage was 2.98%, for the 0 mm – 150 mm depth, and 3.53%, for the 150 mm – 300 mm depth.

The mean bulk density of the exact soil area where the second trial was laid out, at planting, was 1.39 g.cm^{-3}, for the 0 mm – 150 mm depth, and 1.70 g cm^{-3}, for the 150 mm – 300 mm depth. The mean volumetric soil moisture percentage was 9.00%, for the 0 mm – 150 mm depth, and 7.43%, for the 150 mm – 300 mm depth.

5.2.4 Experimental design and trial management

Fourteen different canola cultivars that were available on the South African retail seed market for the year 2020, were obtained from various seed marketing companies. In this trial all 14 canola cultivars were planted within different conservation agriculture (CA) systems. The trial focused on differences between cultivars in terms of their establishment, growth and yield parameters. For the sake of confidentiality, the 14 cultivars were randomly assigned a code number from 1 to 14. In the results and discussion only the code numbers are going to be mentioned.

All the trials were laid out in randomised block designs. The cultivars acted as the treatment variable and were randomised in three blocks for each trial. Each plot planted had an initial area of 14.7 m^2 (2.1 m width x 7 m length). Plots were measured and marked, at each trial site, to ensure accurate planting and data collection. The trial was repeated twice at both Tygerhoek research farm and Langgewens research farm, with different planting times. The earlier planting dates were named as Tygerhoek I and Langgewens I, where the later planting dates were named Tygerhoek II and Langgewens II. In Table 5.1 all the planting dates are represented as the canola trials were planted at every trial site.

A no-till tine planter with knife-point openers (300 mm row-spacing) was used to plant canola at all the trial sites at an average depth of between 10 mm and 15 mm. In Table 5.2 the number of seeds planted per plot, for each cultivar, over all the trial sites are shown. The values were at a constant when working with TSM values as indicated on product labels. The actual TSM of each seed lot was later tested and the exact number of seeds planted per plot and per square meter could be determined. The last two columns of Table 5.2 indicate the 50% and 70% values of seeds planted per square meter to be used as described in section 5.2.5.1.

Crop and pest management throughout the season at all trial sites were done by means of current best-known practices per region.

Table 5.1: Planting dates of 2020 canola trials across the Western Cape of South Africa as per trial

Trial site:	Planting date:
Tygerhoek I	07/05/2020
Tygerhoek II	22/05/2020
Riversdale	20/05/2020
Langgewens I	11/05/2020
Langgewens II	02/06/2020
Hopefield	18/05/2020

Table 5.2: Planting details of 14 canola cultivars in trials planted across the Western Cape of South Africa

Cultivar no.	Thousand Seed Mass	Plot area	Weight of seeds per plot	Seeds per plot	Seeds per m²	50% seeds per m²	70% seeds per m²
Conventional Cultivars	*(g)*	*(m²)*	*(g)*				
6	4.746	14.7	5.8	1222.1	83.1	41.6	58.2
8	3.644	14.7	5.3	1454.4	98.9	49.5	69.2
13	4.132	14.7	5.8	1403.7	95.5	47.75	66.85
14	4.502	14.7	6.4	1421.6	96.7	48.35	67.7
Clearfield (CL) Cultivars							
1	5.216	14.7	7.6	1457.1	99.1	49.6	69.4
2	4.802	14.7	6.4	1332.8	90.7	45.35	63.5
3	4.302	14.7	6.4	1487.7	101.2	50.6	70.84
4	4.758	14.7	6.4	1345.1	91.5	45.75	64.05
Triazine Tolerant (TT) Cultivars							
5	4.008	14.7	5.3	1322.4	90.0	45.0	63.0
7	5.953	14.7	8.2	1377.5	93.7	46.85	65.6
9	3.982	14.7	5.8	1456.6	99.1	49.6	69.4
10	5.596	14.7	8.2	1465.3	99.7	49.9	69.8
11	3.366	14.7	4.1	1218.1	82.9	41.5	58.03
12	4.728	14.7	6.4	1353.6	92.1	46.1	64.47

5.2.5 Data collection

5.2.5.1 Plant population

Plant populations of each plot for each trial was determined 14 days after first emergence (DAE) and 45 DAE. Plant populations at the 14 DAE evaluation gives an indication of field emergence and the 45 DAE evaluation gives a field establishment indication. Plant populations were determined by counting the number of plants in a random one-meter row and converting it to plants per square meter. Ten random one-meter rows were counted per plot for each trial to determine the mean plants per square meter (plants m^{-2}) for each plot.

The conversion from plants per meter (plants m^{-1}) to plants per square meter (plants m^{-2}) was done by means of the following equation as described by the GRDC (2018a):

$$Plants\ m^{-2} = \frac{plants\ m^{-1}}{Planted\ row\ spacing\ (m)}$$

where:

$Planted\ row\ spacing\ (m)$ = 0.3

Harker et al. (2012) and the Protein Research Foundation (2018) reported that generally only 50-70% of planted canola seeds will eventually emerge and establish into productive plants. Therefore, each mean plant population per evaluation was categorised within three categories according to the number of emerged seeds (plant population) compared to the number of planted seeds per square meter. Categories are classified as >70% of planted seeds emerged (high), 50 – 70% of planted seeds emerged (medium) and <50% of planted seeds emerged (low). The 50% and 70% values of seeds planted per square meter used to compare to plant population results are indicated in Table 5.2. The values shown in Table 5.3 are however the actual counts of plants per square meter but the classes into which they were classified into were according to the percentage of seeds that emerged and established as seedlings as explained above.

Cultivar field emergence rankings was determined in order to rank the cultivars in terms of emergence/establishment. Each category was allocated a performance value, high = 1, medium = 2 and low = 3, and the sum of these values per cultivar over all six localities was used to assign rankings. The cultivars were then assigned a ranking from 1 to 14 according to performance categories per cultivar across all trials.

5.2.5.2 Relationships between seed quality and vigour parameters towards mean plant populations

All the tested general seed quality and vigour parameters from Chapters 3 and 4 were correlated to the mean plant population results, for all the trials, at 14 DAE and 45 DAE evaluations to determine which parameter had the best relationship with field emergence results (14 DAE) and field establishment results (45 DAE) as predicting variables.

This comparison was done by means of a pairwise multiple regression on all the testing parameters, to determine the relationship of each parameter to plant population results. The results are represented in Table 5.4 which show the coefficient of determination (R^2) values for each interaction combination of all the tested parameters.

5.2.5.3 Biomass and Leaf Area Index (LAI)

Aboveground biomass samples were collected at 14, 45 and 90 days after first emergence (DAE) by cutting plants down at ground level. Ten random plants per plot were sampled at 14 DAE and five random plants per plot at 45 and 90 DAE. The leaves from all the plants per plot were separated from the stems and leaf area was determined by means of a LI-COR area meter (model – 3100) at each sampling date. The LAI was subsequently calculated using the plant populations for each plot. The same plants, stems and leaves, were then dried at 60 °C until a constant weight was reached, after approximately 72 hours. After drying the plants, weights were determined and the subsequent aboveground dry biomass production at 14, 45 and 90 DAE was calculated per hectare (ha) by means of plant population data.

The equation used to determine leaf area index (LAI) by means of plant population data as described by Blanco and Folegatti (2003):

$$Leaf\ Area\ Index\ (LAI) = \frac{\chi}{10\ 000} \times Plants\ m^{-2}$$

where:

χ = Mean leaf area (cm^2) per plant

$Plants\ m^{-2}$ = Mean plant population per square meter

Biomass per hectare was determined by means of the following conversion equation:

$$Biomass\ (kg\ ha^{-1}) = \beta \times Plants\ m^{-2} \times 10\ 000$$

where:

β = Mean dry biomass weight (kg) per plant

$Plants\ m^{-2}$ = Plant population per square meter

5.2.5.4 Yield

All six trials at the 4 locations were harvested between 4 November 2020 and 19 November 2020 with a 1.5 m wide Wintersteiger plot combine. The combine makes use of reaping, threshing, and winnowing processes to separate seed from plants and clean the seed from chaff. The clean seed from each plot was collected and subsequently used to determine the yield by weighing the seed of each plot and converting the value to yield (kg ha^{-1}). Yield (kg ha^{-1}) was determined by means of the following conversion equation:

$$Yield\ (kg\ ha^{-1}) = \alpha \times \frac{10\ 000\ m^2}{Area\ harvested\ (m^2)}$$

where:

α = Weight of seed collected per plot (kg)

5.2.6 Relationships of selected seed characteristics and plant growth parameters towards mean yield

All the seed quality and vigour testing parameters, from Chapters 3 and 4, that had the highest effect on 14 DAE and 45 DAE plant populations was identified in Table 5.4 in section 5.3.2. Only the parameters with the highest effect on plant populations, together with plant populations, biomass and LAI were correlated with the mean yield results for all the trials, to determine which parameter had the best relationship with the final yield.

This comparison was done by means of a pairwise multiple regression between germination percentage, glasshouse emergence, 24 hour accelerated ageing (AA) germination percentage, 24 hour accelerated ageing (AA) emergence percentage, planting depth (10 mm), planting depth (20 mm), drought stress, 14 DAE plant populations, 45 DAE plant populations, mean biomass, LAI and mean yield results to determine the relationship of each parameter towards yield results. The results are represented in Table 5.12 which shows the coefficient of determination (R^2) for each interaction combination of all the tested parameters.

5.2.7 Statistical analyses

Statistical analysis was performed by means of STATISTICA version 13.6.0 (TIBCO 2019). All the data was subjected to analysis of variance (ANOVA) to determine if there were any differences between cultivars, cultivar treatments and cultivar performance.

All the field trials were laid out as a randomised block design and underwent general linear mixed models (GLMM) analysis to determine differences between cultivars, at each evaluation, with regards to plant population, biomass, LAI and yield. The two factors of the two-way ANOVA were the cultivars (treatment) and the blocking factor.

Fisher’s least significant difference (LSD) was calculated at the 5% level to compare treatment means. A probability level of 5% was considered significant for all significance tests.

5.3 Results

5.3.1 Plant population

Several differences were recorded between the different canola cultivars tested with regards to their plant populations. Cultivars are represented in their three groups, representing their herbicide resistance traits for each trial and includes a mean plant population column. Plant populations are represented for two evaluation times when plant counts were done (14 DAE and 45 DAE), per cultivar and statistically analysed per evaluation time with regards to plant population values (Table 5.3).

The plant populations for each evaluation is described below by dividing the results into three categories, high, medium and low, with regards to the percentage of seeds planted (Table 5.2) that actually emerged i.e. plant population (Table 5.3). Cultivars from different categories do not necessarily differ significantly ($p<0.05$) with regards to plant populations, which can be seen in Table 5.3. Categories are classified as >70% of planted seeds emerged per square meter (high), 50 – 70% of planted seeds emerged per square meter (medium) and <50% of planted seeds emerged per square meter (low). The numbers of seeds planted were indicated earlier in this chapter in section 5.2.4. (Table 5.2)

At Riversdale at the 14 DAE evaluation Cultivars 5 and 7 recorded the highest emergence of all the cultivars tested (Table 5.3). Cultivars 8, 10 and 14 recorded the lowest emergence with all the other cultivars scattered in the medium performance category. The only statistically significant differences occurred with Cultivars 5, 7 and 9 showing a significantly higher number of emerged seedlings than Cultivars 8 and 14. The 45 DAE evaluation recorded Cultivars 1, 3, 4, 8, 10, 11, 12 and 14 as all being in the lowest performing category, with an establishment percentage of less than 50% of planted seed per square meter (Table 5.2). For the 45 DAE evaluation at Riversdale, no high category (>70% emergence) was recorded and Cultivars 2, 5, 6, 7, 9 and 13 were all within the medium performance category (50 – 70% emergence). Cultivar 9 was the only cultivar in the medium category that had significantly more seedlings than all the cultivars in the low category.

At the 14 DAE evaluation at the Hopefield trial Cultivars 3, 4, 8, 9 and 14 indicated field emergence percentages of below 50% of planted seeds per square meter (Table 5.3), falling within the lowest performing category. None of the tested cultivars recorded emergence values within the high performing category and all the other cultivars were categorised within the medium performance category. Cultivar 14 had significantly lower plant numbers compared to all the other cultivars tested. For the 45 DAE evaluation, Cultivar 13 was the only cultivar categorised in the high performing category having significantly more plants than all the cultivars in the lowest category and Cultivars 5 and 11 in the medium performance category. Cultivars 1, 2, 3, 5, 6, 7, 11 and 12 were all within the medium category. The lowest performing cultivars at the 45 DAE evaluation for the Hopefield trial were Cultivars 4, 8, 9, 10 and 14, with Cultivar 14 performing significantly worse than all the cultivars in the medium category.

For the Tygerhoek I trial at the 14 DAE evaluation only Cultivars 7, 8 and 11 recorded field emergence values below 50% of planted seeds per square meter (Table 5.3). Cultivars 1, 2, 3, 4, 9, 10, 12, 13 and 14 were all categorised in the medium performance category (50 – 70% emergence). Cultivar 5 and 6 were the only cultivars to record a field emergence above 70% of planted seeds after 14 DAE and the plant numbers were significantly higher than all the cultivars in the low category. At the 45 DAE evaluation several cultivars showed plant populations dropping to below the 50% field establishment percentage of the planted seeds per square meter (Table 5.2). The cultivars that were categorised within this lowest performance category included Cultivars 1, 3, 4, 7, 8, 9, 10, 11, 13 and 14. Cultivars 2, 5, 6 and 12 were categorised in the medium performance category and no high category was recorded. The only significant differences that occurred at 45 DAE were between Cultivars 2, 5 and 12, in the medium, category and Cultivar 8 in the low category.

Tygerhoek II was the last trial planted and also showed the best overall emergence and establishment results of all the trials. For the 14 DAE evaluation only Cultivars 8 and 13 recorded values in the low performing category. Cultivars 2, 5, 6, 7 and 12 all showed emergence percentages above 70% of planted seeds per square meter (Table 5.3), subsequently making them high performing cultivars which were all statistically better than Cultivars 8 and 13 in the low category. All the other cultivars were categorised as medium performing cultivars, with field emergence percentages of between 50 – 70% of planted seeds per square meter (Table 5.2). At the 45 DAE evaluation only Cultivar 8 was below 50% field establishment, with Cultivars 5, 12 and 13 being in the highest performing category (>70% of planted seeds per square meter). All the other cultivars were scattered within the medium performance category. The cultivars in the highest performance category had statistically higher plant counts than Cultivar 8 in the lowest category and also Cultivars 1, 2, 4, 14 and 11 in the medium performance category.

At the Langgewens I trial, none of the cultivars recorded values within the high-performance category, at both the 14 DAE and 45 DAE evaluations Table 5.3). At the 14 DAE evaluation, Cultivars 1, 4, 7, 8, 9, 10 and 14 were categorised within the lowest performing category. Cultivar 8 had significantly lower numbers of plants than all the other cultivars except for Cultivar 14. For the 45 DAE evaluation Cultivars 2, 11 and 13 were added to these low performing cultivars. Again Cultivar 8 had statistically less plants established than the other cultivars, except Cultivars 4, 10 and 14. All the other cultivars for both these evaluations were categorised within the medium performance category.

The second trial planted at Langgewens, at the later planting date (Langgewens II), showed that Cultivars 5 and 13 were the highest performing cultivars at the 14 DAE evaluation (Table 5.3). Cultivars 7, 8, 9, 10 and 14 were the lowest performing cultivars with regards to plant populations at 14 DAE. Cultivars 1, 2, 3, 4, 6, 11 and 12 all recorded values within the medium performance category. Cultivars 5 and 13 performed significantly better, with regards to plant population, than all the cultivars in the low category and some cultivars in the medium category. At 45 DAE several cultivars dropped down to the lowest performing category and these included Cultivars 1, 4, 5, 7, 8, 9, 10, 11, 12 and 14. Cultivars 2, 3, 6 and 13 were all within the medium performance category with no cultivar recorded in the high-performance category at the 45 DAE evaluation for Langgewens II. Cultivar 13 had significantly more plants established than all the other cultivars apart from Cultivar 2.

The mean population data for all the trials were combined and compared to establish an overall result for each cultivar Table 5.3). The mean populations at the 14 DAE evaluation recorded Cultivar 5 to be the only cultivar to be categorised within the highest performing category. Cultivar 5 performed significantly better than all the cultivars in the low category and Cultivars 1, 3, 4, 7, 9 and 11 in the medium category. Cultivars 1, 2, 3, 4, 6, 7, 9, 11, 12 and 13 were all within the medium performing category, showing mean field emergence values of between 50% and 70% of planted seeds per square meter (Table 5.2). The three cultivars that had the lowest mean field emergence performance over all the trials after 14 DAE were Cultivars 8, 10 and 14. These three cultivars all recorded emergence values, at the 14 DAE evaluation, below 50% of seeds planted (Table 5.2). At 45 DAE, none of the cultivars were categorised in the high-performance category. Cultivar 5 fell back into the medium performance category and Cultivars 1, 4 and 10 to the low performance category. Thus, the cultivars categorised as medium performing cultivars over all trials were Cultivars 2, 3, 5, 6, 7, 11, 12 and 13. The lowest performing cultivars with regards to mean plant populations at 45 DAE were Cultivars 1, 4, 8, 10, 11 and 14. Cultivar 13 had significantly higher plant numbers than all other cultivars apart from Cultivars 2, 5 and 12.

The final cultivar field emergence rankings showed that Cultivars 8 and 14 were ranked the lowest with regards to plant populations and subsequently field establishment (Table 5.3). Cultivars 5, 6 and 13 were the top three performing cultivars and were ranked 1st ,2nd and 3rd, respectively.

5.3.2 Relationships between seed quality and vigour parameters towards mean plant populations

Table 5.4 depicts all the pairwise coefficient of determination (R^2) values for all the general seed quality and seed vigour tested parameters (Chapter 3 and 4) towards plant populations at 14 DAE and 45 DAE. For the 14 DAE plant population parameter the parameters that showed a moderate effect ($0.5 < R^2 < 0.7$), according to Moore et al. (2013), were germination percentage, glasshouse emergence, accelerated ageing (AA) germination (24 hours), accelerated ageing (AA) emergence (24 hours) planting depth (10 mm), planting depth (20 mm) and the drought stress test (Table 5.4). The 45 DAE plant population recorded an R^2 value higher than 0.7 with the 14 DAE, indicating a strong relationship, but cannot be used to predict field emergence since 45 DAE plant population are in fact the field establishment results that are obtained after the 14 DAE emergence results.

The glasshouse emergence, AA germination (24 hours), AA emergence (24 hours) planting depth (10 mm), planting depth (20 mm) and the drought stress parameters all recorded R^2 values between 0.5 - 0.7, indicating moderate effects, towards the 45 DAE plant population parameter. The 14 DAE plant population recorded an R^2 value higher than 0.7, indicating a strong relationship, but it does not really make sense to use this to predict field establishment since 14 DAE plant population is in fact the field emergence results and nothing can be done at that stage to influence the establishment percentage.

The only difference between parameters that had a significant effect at 14 DAE and 45 DAE is that germination percentage has a moderate effect ($0.5 < R^2 < 0.7$) on 14 DAE plant populations but a weak effect ($R^2 < 0.5$) at 45 DAE.

The glasshouse emergence parameter showed the highest relationship with the 45 DAE plant population. The R^2 value, of 0.743, shows a strong effect ($R^2 > 0.7$) according to Moore et al. (2013).

All the other tested parameters showed weak interactions ($R^2 < 0.5$) towards the mean plant populations values recorded at 14 and 45 DAE.

Table 5.3: Mean plant populations of 14 canola cultivars in 2020, at six field trials at 14 and 45 days after first emergence (DAE). Cells with green and red shading indicate the highest (>70% emergence of planted seeds) class and lowest (<50% emergence of planted seeds) class of seeds emerged/established per column, respectively

Cultivar no.	Riversdale		Hopefield		Tygerhoek I		Tygerhoek II		Langgewens I		Langgewens II		Mean Populations		Cultivar field emergence ranking
	14 DAE	45 DAE	14 DAE	45 DAE	14 DAE	45 DAE	14 DAE	45 DAE	14 DAE	45 DAE	14 DAE	45 DAE	14 DAE	45 DAE	
Conventional Cultivars							*(plants m^{-2})*								
6	54.2^{ab}	45.3^{bcdef}	52.4^{ab}	54.4^{abc}	73.9^{a}	45.5^{ab}	66.7^{abc}	55.1^{bcd}	45.3^{abcd}	46.7^{ab}	52.7^{abcde}	43.8^{bcd}	57.5^{abcd}	48.1^{bcd}	2
8	40.9^{b}	39.8^{cdef}	36.9^{c}	39.8^{cd}	29.2^{e}	27.3^{b}	46.7^{d}	48.4^{d}	23.8^{e}	21.6^{e}	28.4^{f}	27.1^{e}	34.6^{h}	34.0^{g}	14
13	59.3^{ab}	55.3^{abc}	54.2^{a}	70.2^{a}	59.7^{abc}	45.3^{ab}	44.4^{d}	68.0^{a}	52.4^{abc}	43.3^{ab}	66.7^{a}	60.0^{a}	59.8^{ab}	57.1^{a}	3
14	40.2^{b}	30.2^{f}	20.0^{d}	23.1^{d}	50.6^{bcd}	38.7^{ab}	60.2^{bcd}	53.3^{cd}	36.2^{de}	32.0^{cde}	44.7^{de}	33.1^{de}	42.0^{g}	35.7^{fg}	13
Clearfield (CL) Cultivars															
1	56.4^{ab}	40.7^{cdef}	58.9^{a}	61.3^{ab}	62.5^{abc}	38.9^{ab}	56.7^{cd}	50.9^{d}	44.7^{abcd}	42.0^{abc}	52.0^{bcde}	44.0^{bcd}	55.2^{bcde}	46.4^{bcde}	9
2	59.1^{ab}	57.8^{ab}	49.8^{ab}	53.1^{abc}	66.1^{ab}	50.0^{a}	66.0^{abc}	54.4^{cd}	53.5^{abc}	45.3^{ab}	60.9^{abc}	51.3^{ab}	59.3^{abc}	52.7^{ab}	4
3	52.4^{ab}	39.5^{cdef}	47.8^{abc}	62.2^{ab}	60.3^{abc}	45.6^{ab}	68.2^{abc}	62.9^{abc}	55.3^{ab}	46.7^{ab}	50.7^{bcde}	40.7^{bcd}	55.8^{bcde}	49.6^{bc}	6
4	53.1^{ab}	40.4^{cdef}	41.8^{bc}	44.7^{bc}	52.8^{bc}	36.2^{ab}	49.5^{cd}	49.8^{d}	44.4^{abcd}	29.4^{de}	49.8^{cde}	38.2^{cde}	48.6^{efg}	39.6^{efg}	10
Triazine Tolerant (TT) Cultivars															
5	66.2^{a}	54.0^{abcd}	55.3^{a}	51.6^{bc}	63.9^{ab}	52.6^{a}	80.4^{a}	66.0^{ab}	55.9^{a}	51.8^{a}	64.4^{ab}	42.7^{bcd}	64.9^{a}	52.7^{ab}	1
7	68.9^{a}	50.5^{abcde}	50.0^{ab}	61.1^{ab}	42.2^{cde}	38.4^{ab}	66.9^{abc}	56.2^{bcd}	42.9^{bcd}	40.7^{bc}	40.5^{ef}	45.1^{bcd}	51.9^{cdef}	48.3^{bcd}	7
9	64.2^{a}	62.0^{a}	40.7^{bc}	41.3^{cd}	55.3^{abc}	41.3^{ab}	63.6^{abcd}	59.1^{abcd}	39.3^{cd}	36.4^{bcd}	43.1^{de}	34.7^{cde}	51.0^{def}	45.6^{bcde}	11
10	49.8^{ab}	37.8^{ef}	50.0^{ab}	49.1^{bc}	52.5^{bc}	41.1^{ab}	55.7^{cd}	57.8^{abcd}	41.6^{bcd}	29.3^{de}	47.8^{cde}	45.8^{bc}	49.6^{ef}	43.3^{cde}	12
11	52.4^{ab}	38.4^{def}	48.2^{abc}	50.6^{bc}	31.4^{de}	34.0^{ab}	55.8^{cd}	54.2^{cd}	41.8^{bcd}	37.4^{bcd}	45.1^{de}	37.1^{cde}	45.8^{fg}	42.0^{def}	8
12	62.9^{ab}	43.8^{bcdef}	55.8^{a}	62.4^{ab}	57.5^{abcd}	50.5^{a}	76.5^{ab}	68.2^{a}	59.1^{a}	51.5^{a}	57.1^{abcd}	36.2^{cde}	61.5^{ab}	52.1^{ab}	5

*Distinct letters above values within a column indicate significant ($p<0.05$) differences between plant populations

Table 5.4: Coefficient of determination (R^2) values for each pairwise interaction combination towards the plant population results of all the general seed quality and seed vigour parameters used for assessing 14 canola cultivars of South Africa for the year 2020. Cells with red shading indicate all R^2 values between 0.5 – 0.7 (moderate effect) and green shading values above 0.7 (strong effect) within the mean plant population parameters for the 14 DAE and 45 DAE evaluations. Parameters were numbered from 1 – 19 within the table and described below

Seed Quality Parameters	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	**18**	**19**
1	**1**	0.594	0.821	0.821	0.118	0.017	0.056	0.035	0.335	0.212	0.000	0.000	0.012	0.005	0.347	0.328	0.000	**0.070**	**0.019**
2	0.594	**1**	0.718	0.743	0.178	0.095	0.167	0.030	0.100	0.258	0.008	0.000	0.064	0.068	0.399	0.049	0.050	**0.193**	**0.099**
3	0.821	0.718	**1**	0.999	0.036	0.001	0.021	0.015	0.248	0.112	0.000	0.000	0.005	0.000	0.268	0.145	0.000	**0.041**	**0.019**
4	0.821	0.743	0.999	**1**	0.041	0.003	0.026	0.016	0.243	0.120	0.001	0.000	0.007	0.000	0.278	0.141	0.000	**0.047**	**0.022**
5	0.118	0.178	0.036	0.041	**1**	0.685	0.925	0.457	0.142	0.853	0.384	0.000	0.715	0.851	0.579	0.243	0.659	**0.520**	**0.483**
6	0.017	0.095	0.001	0.003	0.685	**1**	0.732	0.490	0.058	0.782	0.535	0.000	0.660	0.803	0.286	0.077	0.586	**0.655**	**0.743**
7	0.056	0.167	0.021	0.026	0.925	0.732	**1**	0.443	0.135	0.834	0.417	0.000	0.705	0.863	0.574	0.179	0.708	**0.540**	**0.566**
8	0.035	0.030	0.015	0.016	0.457	0.490	0.443	**1**	0.391	0.589	0.850	0.000	0.540	0.512	0.336	0.109	0.406	**0.277**	**0.330**
9	0.335	0.100	0.248	0.243	0.142	0.058	0.135	0.391	**1**	0.229	0.164	0.000	0.060	0.039	0.456	0.583	0.010	**0.000**	**0.002**
10	0.212	0.258	0.112	0.120	0.853	0.782	0.834	0.589	0.229	**1**	0.520	0.000	0.646	0.771	0.562	0.201	0.562	**0.653**	**0.668**
11	0.000	0.008	0.000	0.001	0.384	0.535	0.417	0.850	0.164	0.520	**1**	0.000	0.669	0.564	0.153	0.021	0.534	**0.295**	**0.463**
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**1**	0.000	0.000	0.000	0.000	0.000	**0.000**	**0.000**
13	0.012	0.064	0.005	0.007	0.715	0.660	0.705	0.540	0.060	0.646	0.669	0.000	**1**	0.761	0.290	0.053	0.817	**0.510**	**0.596**
14	0.005	0.068	0.000	0.000	0.851	0.803	0.863	0.512	0.039	0.771	0.564	0.000	0.761	**1**	0.346	0.078	0.855	**0.571**	**0.630**
15	0.347	0.399	0.268	0.278	0.579	0.286	0.574	0.336	0.456	0.562	0.153	0.000	0.290	0.346	**1**	0.352	0.247	**0.239**	**0.172**
16	0.328	0.049	0.145	0.141	0.243	0.077	0.179	0.109	0.583	0.201	0.021	0.000	0.053	0.078	0.352	**1**	0.017	**0.000**	**0.000**
17	0.000	0.050	0.000	0.000	0.659	0.586	0.708	0.406	0.010	0.562	0.534	0.000	0.817	0.855	0.247	0.017	**1**	**0.512**	**0.594**
18	**0.070**	**0.193**	**0.041**	**0.047**	**0.520**	**0.655**	**0.540**	**0.277**	**0.000**	**0.653**	**0.295**	**0.000**	**0.510**	**0.571**	**0.239**	**0.000**	**0.512**	**1**	**0.868**
19	**0.019**	**0.099**	**0.019**	**0.022**	**0.483**	**0.743**	**0.566**	**0.330**	**0.002**	**0.668**	**0.463**	**0.000**	**0.596**	**0.630**	**0.172**	**0.000**	**0.594**	**0.868**	**1**

* 1 = Thousand Seed Mass
2 = Seed Size Fractioning (<1.7 mm)
3 = Seed Size Fractioning (1.7 mm – 2.0 mm)
4 = Seed Size Fractioning (<1.7 mm)
5 =Germination Percentage
6 = Glasshouse Emergence
7 = Accelerated Ageing germination (24hours)
8 = Accelerated Ageing germination (48hours)
9 = Accelerated Ageing germination (72hours)
10 = Accelerated Ageing emergence (24hours)
11 = Accelerated Ageing emergence (48hours)
12 = Accelerated Ageing emergence (72hours)
13 = Planting Depth (10 mm)
14 = Planting Depth (20 mm)
15 = Planting Depth (40 mm)
16 = Planting Depth (60 mm)
17 = Drought Stress
18 = Plant Population (14 DAE)
19 = Plant Population (45 DAE)

5.3.3 Biomass

The biomass results at 14, 45 and 90 days after first emergence (DAE) are represented in Tables 5.5, Table 5.6 and Table 5.7, respectively. Several differences were recorded between cultivars at each evaluation for each trial site. Cultivars are represented in their three groups, representing their herbicide resistance traits. Statistical analysis was done on each trial to determine differences between cultivars, including the mean biomass across all trials, at the separate evaluations.

The biomass results for each trial and evaluation is described below by dividing results in three performance categories, high, medium and low with regards to the mean biomass. Cultivars from different categories do not necessarily differ significantly ($p<0.05$), which can be seen in Table 5.5, Table 5.6 and Table 5.7. Categories for the biomass at the 14 DAE evaluation are classified as >40 kg ha^{-1} (high), 20 – 40 kg ha^{-1} (medium) and <20 kg ha^{-1} (low). Categories at 45 DAE is classified as >1400 kg ha^{-1} (high), 700 – 1400 kg ha^{-1} (medium) and <700 kg ha^{-1} (low). For the final evaluation at 90 days after first emergence (DAE) categories are classified as >10 000 kg ha^{-1} (high), 5000 – 10 000 kg ha^{-1} (medium) and <5000 kg ha^{-1} (low).

At 14 DAE Cultivar 2 recorded the best overall mean biomass across all the trial sites and was the only cultivar categorised within the high-performance category (Table 5.5). Cultivars 8, 9, 11 and 14 were the lowest performing cultivars overall with regards to mean biomass at 14 DAE, all recording biomass values below 20 kg ha^{-1} and being significantly ($p<0.05$) lower than Cultivar 2. Other cultivars not specifically mentioned were all categorised within the medium performance category.

At 45 days after first emergence (DAE) Cultivar 2 was again the cultivar with the highest mean biomass across all trials, although not significantly better than Cultivars 1, 3, 6 and 13. Cultivars 1, 3, 4, 5, 6, 7, 9, 10, 12 and 13 were all within the medium performance category with Cultivars 1, 6 and 13 performing especially well in several trials (Table 5.6). The cultivars with the lowest mean biomass after 45 DAE was Cultivars 8, 11 and 14. Cultivar 11 is grouped in the TT cultivar group and was expected to have lower biomass values.

The final biomass values recorded before harvesting was at 90 DAE. Cultivar 8 was the lowest performing cultivar with a mean biomass value of only 4511.5 kg ha^{-1}, even lower than all the TT cultivars. Although Cultivar 8 was the only cultivar in the low performance category, the cultivar did not have significantly lower biomass than any of the TT cultivars or Cultivar 14 (Table 5.7). Cultivars 1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12 and 14 were all within the medium performance category. Cultivar 14 was at the lower spectrum of the medium performing cultivars together with the TT cultivars, which is unexpected for a Conventional cultivar. Cultivar 13 showed the highest mean overall biomass across all trials at 90 DAE (10064,7 kg ha^{-1}), and the only other cultivars that did not differ significantly from it were Cultivars 2, 3 and 6.

Table 5.5: Mean biomass (kg ha^{-1}) of 14 canola cultivars of South Africa, for the year 2020, at six field trials 14 days after first emergence (DAE). Cells with green and red shading indicate the highest (>40 kg ha^{-1}) and lowest (<20 kg ha^{-1}) performing values per column, respectively

Cultivar no.	Riversdale	Hopefield	Tygerhoek I	Tygerhoek II	Langgewens I	Langgewens II	Mean Biomass
Conventional Cultivars				*(kg ha^{-1})*			
6	44.5^{bcde}	37.7^{a}	35.8^{a}	38.9^{a}	26.6^{abcd}	27.7^{bc}	35.2^{abc}
8	13.1^{ef}	14.7^{fg}	6.0^{e}	14.8^{e}	6.1^{j}	6.9^{g}	10.3^{g}
13	63.6^{ab}	35.5^{ab}	18.7^{bcd}	25.2^{cde}	28.8^{abc}	37.0^{ab}	34.8^{abc}
14	10.6^{f}	7.0^{g}	8.4^{de}	18.5^{de}	8.6^{ij}	10.6^{efg}	10.6^{g}
Clearfield (CL) Cultivars							
1	68.7^{ab}	31.7^{abc}	32.7^{a}	37.4^{ab}	24.9^{abcde}	40.4^{a}	39.3^{ab}
2	86.4^{a}	27.6^{bcd}	30.8^{ab}	39.7^{a}	31.4^{a}	34.7^{ab}	41.8^{a}
3	50.9^{bcd}	23.0^{cdef}	13.9^{cde}	33.3^{abc}	23.4^{bcdef}	17.3^{def}	27.0^{cde}
4	59.9^{abc}	19.1^{def}	20.3^{bcd}	26.2^{bcde}	19.1^{efg}	28.9^{bc}	28.9^{cde}
Triazine Tolerant (TT) Cultivars							
5	20.4^{def}	18.6^{def}	24.3^{abc}	28.8^{abcd}	22.1^{cdef}	23.0^{cd}	22.9^{def}
7	69.7^{ab}	22.5^{def}	14.3^{cde}	37.7^{ab}	20.7^{defg}	22.0^{cd}	31.1^{bcd}
9	23.1^{def}	17.7^{ef}	15.0^{cde}	18.8^{de}	11.4^{hij}	10.2^{fg}	16.0^{fg}
10	20.4^{def}	24.5^{cde}	13.8^{cde}	25.0^{cde}	17.2^{fgh}	20.5^{cde}	20.2^{efg}
11	22.9^{def}	16.6^{ef}	8.4^{de}	16.8^{de}	14.1^{fghi}	15.2^{defg}	15.7^{fg}
12	28.6^{cdef}	21.0^{def}	15.6^{cde}	35.7^{abc}	29.8^{ab}	22.8^{cd}	25.6^{cdef}

*Distinct letters above values within a column indicate significant (p<0.05) differences

Table 5.6: Mean biomass (kg ha^{-1}) of 14 canola cultivars of South Africa, for the year 2020, at six field trials 45 days after first emergence (DAE). Cells with green and red shading indicate the highest (>1400 kg ha^{-1}) and lowest (<700 kg ha^{-1}) performing values per column, respectively

Cultivar no.	Riversdale	Hopefield	Tygerhoek I	Tygerhoek II	Langgewens I	Langgewens II	Mean Biomass
Conventional Cultivars				*(kg ha^{-1})*			
6	1131.4^{ab}	1353.2^{abc}	558.8^{ab}	1450.2^{abcde}	1973.1^{ab}	1152.4^{ab}	1269.8^{abc}
8	696.0^{bc}	509.3^{cd}	513.6^{ab}	1124.1^{cde}	597.6^{e}	344.0^{d}	630.7^{e}
13	910.8^{abc}	1382.8^{a}	1250.2^{ab}	1819.2^{abcd}	1241.7^{cde}	1362.6^{a}	1327.9^{ab}
14	448.7^{c}	340.0^{d}	650.2^{ab}	1070.1^{de}	583.7^{e}	480.5^{cd}	595.5^{e}
Clearfield (CL) Cultivars							
1	881.7^{abc}	1368.9^{ab}	578.9^{ab}	2038.1^{ab}	2205.0^{a}	1217.8^{a}	1381.7^{ab}
2	1294.0^{a}	972.5^{abcd}	1284.0^{ab}	1995.4^{abc}	1484.3^{bc}	1480.3^{a}	1418.4^{a}
3	712.5^{bc}	1231.1^{abc}	983.0^{ab}	1645.4^{abcde}	1403.4^{bcd}	601.8^{cd}	1096.2^{abcd}
4	797.8^{abc}	859.4^{abcd}	303.0^{b}	2315.5^{a}	1082.0^{cde}	802.7^{bc}	1026.7^{bcd}
Triazine Tolerant (TT) Cultivars							
5	719.4^{bc}	640.5^{abcd}	1756.1^{a}	1005.1^{de}	996.7^{cde}	417.6^{cd}	922.6^{cde}
7	940.0^{abc}	810.5^{abcd}	624.3^{ab}	1151.7^{cde}	1152.8^{cde}	741.6^{cd}	903.5^{de}
9	758.4^{bc}	522.1^{cd}	1285.2^{ab}	781.0^{e}	807.3^{cde}	358.5^{d}	752.1^{de}
10	663.3^{bc}	526.0^{bcd}	803.1^{ab}	1428.1^{bcde}	734.8^{de}	563.4^{cd}	786.5^{de}
11	556.6^{c}	638.2^{abcd}	383.0^{ab}	955.6^{de}	709.3^{de}	378.7^{d}	603.6^{e}
12	532.0^{c}	603.4^{abcd}	1213.6^{ab}	1518.8^{abcde}	1065.4^{cde}	422.6^{cd}	892.6^{de}

*Distinct letters above values within a column indicate significant ($p<0.05$) differences

Table 5.7: Mean biomass (kg ha^{-1}) of 14 canola cultivars of South Africa, for the year 2020, at six field trials 90 days after first emergence (DAE). Cells with green and red shading indicate the highest (>10 000 kg ha^{-1}) and lowest (<5000 kg ha^{-1}) performing values per column, respectively

Cultivar no.	Riversdale	Hopefield	Tygerhoek I	Tygerhoek II	Langgewens I	Langgewens II	Mean Biomass
Conventional Cultivars				*(kg ha^{-1})*			
6	6880.9^{c}	6611.9^{bc}	11819.1^{a}	8466.9^{cd}	7849.4^{a}	7858.0^{ab}	8247.7^{abc}
8	5054.3^{c}	5641.2^{bc}	4789.5^{cd}	5780.3^{d}	2893.7^{e}	2909.7^{e}	4511.5^{f}
13	8666.4^{bc}	13277.9^{a}	8410.9^{abcd}	13861.6^{ab}	7133.7^{ab}	9037.4^{a}	10064.7^{a}
14	4284.2^{c}	1614.1^{c}	8361.1^{abcd}	7866.3^{cd}	4820.1^{cde}	4355.1^{cde}	5216.8^{def}
Clearfield (CL) Cultivars							
1	12082.2^{ab}	7568.7^{abc}	7040.6^{bcd}	7195.6^{d}	5023.6^{cd}	6083.2^{abcde}	7499.0^{bcd}
2	14070.7^{a}	8245.8^{ab}	9363.2^{abc}	14634.4^{a}	5607.4^{bcd}	7462.6^{abc}	9897.3^{a}
3	6237.4^{c}	13393.1^{a}	10320.9^{ab}	12739.3^{abc}	7239.7^{ab}	5302.5^{bcde}	9205.5^{ab}
4	6380.6^{c}	6265.5^{bc}	5136.4^{cd}	15529.2^{a}	4234.7^{de}	5164.6^{bcde}	7118.5^{bcde}
Triazine Tolerant (TT) Cultivars							
5	7251.0^{c}	4119.6^{bc}	5703.9^{bcd}	7429.1^{d}	6671.8^{abc}	4953.6^{bcde}	6021.5^{cdef}
7	8722.2^{bc}	6165.0^{bc}	5391.3^{cd}	8682.2^{cd}	4974.7^{cd}	6625.7^{abcd}	6760.2^{cdef}
9	8266.9^{bc}	3665.2^{bc}	4418.8^{d}	9340.6^{bcd}	5467.7^{bcd}	3986.9^{de}	5857.7^{def}
10	5809.3^{c}	7557.8^{abc}	5349.7^{cd}	6414.7^{d}	2911.8^{e}	4968.3^{bcde}	5501.9^{def}
11	5276.3^{c}	3773.1^{bc}	4848.9^{cd}	7363.5^{d}	5303.5^{bcd}	3624.4^{de}	5031.6^{ef}
12	5548.1^{c}	3643.5^{bc}	4976.4^{cd}	8113.0^{cd}	7179.9^{ab}	4209.2^{cde}	5378.4^{def}

*Distinct letters above values within a column indicate significant (p<0.05) differences

5.3.4 Leaf area index (LAI)

The LAI results at 14, 45 and 90 days after first emergence (DAE) are presented in Table 5.8, Table 5.9 and Table 5.10, respectively. Several differences were recorded between cultivars at each evaluation for each trial site. Cultivars are represented in their three groups, representing their herbicide resistance traits. Statistical analysis was done on each trial to determine differences between cultivars for each trial, including the mean LAI across all trials, at the separate evaluations.

The LAI results for each trial and evaluation is described below by dividing results in three performance categories, high, medium and low with regards to the mean LAI. Cultivars from different categories do not necessarily differ significantly (p<0.05), which can be seen in Table 5.8, Table 5.9 and Table 5.10. Categories for LAI for the 14 DAE evaluation is classified as >0.07 (high), 0.035 – 0.07 (medium) and <0.035 (low). Categories at 45 DAE are classified as >2.0 (high), 1.0 – 2.0 (medium) and <1.0 (low). For the final evaluation at 90 days after first emergence (DAE) categories were classified as >6.0 (high), 3.0 – 6.0 (medium) and <3.0 (low).

Mean leaf area index values recorded at 14 DAE showed that Cultivars 1, 2, 6 and 13 had the highest LAI values and was therefore grouped within the high-performance category (Table 5.8). Cultivars 3, 4, 5, 6, 7, 9, 10, 11, 12 and 13 were all considered medium performing cultivars and showed higher performance compared to Cultivars 8 and 14, which had the lowest mean LAI values overall.

At 45 DAE Cultivars 1 and 2 were still the cultivars with the highest mean LAI across all trials but not significantly different from Cultivars 6 and 13 (Table 5.9). Within the medium performance category were Cultivars 3, 4, 5, 7, 9, 10, 11 and 12, with Cultivars 4, 7 and 12 performing especially well at several trials (Table 5.9). The cultivars with the lowest mean LAI after 45 DAE were Cultivars 8 and 14.

The mean LAI values and rankings after 90 days showed that cultivars with the lowest mean LAI results were Cultivars 8, 11 and 14 (Table 5.10). However, these three cultivars were not significantly worse than Cultivars 1, 4, 5, 6, 7, 9 and 10. Cultivar 3 showed the highest mean LAI across all the tested cultivars for all trials with Cultivar 2 not significantly worse. All the other cultivars were considered medium performing cultivars.

Table 5.8: Mean Leaf Area Index (LAI) of 14 canola cultivars of South Africa, for the year 2020, at six field trials 14 days after first emergence (DAE). Cells with green and red shading indicate the highest (LAI>0.07) and lowest (LAI<0.035) performing values per column, respectively

Cultivar no.	Riversdale	Hopefield	Tygerhoek I	Tygerhoek II	Langgewens I	Langgewens II	Mean LAI
Conventional Cultivars							
6	0.079^{bcd}	0.077^{a}	0.065^{a}	0.098^{a}	0.066^{ab}	0.076^{cde}	0.077^{ab}
8	0.025^{d}	0.029^{fg}	0.011^{e}	0.032^{f}	0.015^{h}	0.027^{g}	0.023^{e}
13	0.120^{ab}	0.074^{a}	0.035^{cd}	0.057^{def}	0.067^{ab}	0.119^{ab}	0.079^{ab}
14	0.021^{d}	0.014^{g}	0.016^{de}	0.039^{ef}	0.021^{gh}	0.038^{fg}	0.025^{e}
Clearfield (CL) Cultivars							
1	0.126^{ab}	0.070^{ab}	0.057^{ab}	0.079^{abcd}	0.060^{abc}	0.124^{a}	0.086^{a}
2	0.157^{a}	0.056^{bc}	0.045^{bc}	0.088^{ab}	0.071^{a}	0.105^{abc}	0.087^{a}
3	0.097^{abc}	0.053^{bcd}	0.028^{cde}	0.073^{abcd}	0.058^{abcd}	0.062^{defg}	0.062^{bc}
4	0.118^{ab}	0.039^{cdef}	0.033^{cd}	0.058^{de}	0.043^{cdef}	0.085^{bcd}	0.063^{bc}
Triazine Tolerant (TT) Cultivars							
5	0.043^{cd}	0.040^{cdef}	0.043^{bc}	0.070^{bcd}	0.052^{bcd}	0.065^{def}	0.052^{cd}
7	0.122^{ab}	0.050^{cd}	0.023^{de}	0.082^{abcd}	0.049^{cde}	0.068^{def}	0.066^{bc}
9	0.045^{cd}	0.036^{def}	0.029^{cde}	0.043^{ef}	0.028^{fgh}	0.039^{fg}	0.037^{de}
10	0.040^{cd}	0.051^{cd}	0.026^{cde}	0.059^{cde}	0.041^{def}	0.066^{def}	0.047^{cd}
11	0.043^{cd}	0.032^{ef}	0.016^{de}	0.041^{ef}	0.035^{efg}	0.048^{efg}	0.036^{de}
12	0.054^{cd}	0.046^{cde}	0.029^{cde}	0.083^{abc}	0.071^{a}	0.079^{cde}	0.060^{bc}

*Distinct letters above values within a column indicate significant (p<0.05) differences

Table 5.9: Mean Leaf Area Index (LAI) of 14 canola cultivars of South Africa, for the year 2020, at six field trials 45 days after first emergence (DAE). Cells with green and red shading indicate the highest (LAI>2.0) and lowest (LAI<1.0) performing values per column, respectively

Cultivar no.	Riversdale	Hopefield	Tygerhoek I	Tygerhoek II	Langgewens I	Langgewens II	Mean LAI
Conventional Cultivars							
6	1.883[ab]	2.021[abc]	2.213[abc]	2.212[bcde]	2.831[ab]	1.485[bc]	2.108[abc]
8	1.244[bc]	0.759[cd]	0.659[d]	1.726[de]	0.719[g]	0.545[e]	0.942[g]
13	1.652[abc]	2.607[a]	2.224[abc]	2.881[abcd]	2.153[bcde]	1.992[ab]	2.252[ab]
14	0.884[c]	0.613[d]	1.204[bcd]	1.812[de]	0.957[fg]	0.698[de]	1.028[g]
Clearfield (CL) Cultivars							
1	1.537[abc]	2.499[ab]	2.338[ab]	3.357[abc]	3.289[a]	1.722[ab]	2.457[a]
2	2.253[a]	1.803[abcd]	2.589[a]	3.416[ab]	2.749[abc]	2.078[a]	2.481[a]
3	1.223[bc]	2.114[abc]	1.492[abcd]	3.112[abc]	2.366[abcd]	0.922[de]	1.872[bcd]
4	1.396[abc]	1.543[abcd]	1.449[abcd]	3.614[a]	1.505[defg]	1.151[cd]	1.776[cd]
Triazine Tolerant (TT) Cultivars							
5	1.349[abc]	1.375[abcd]	0.873[cd]	1.727[de]	1.725[cdefg]	0.669[de]	1.286[efg]
7	1.803[ab]	1.747[abcd]	1.265[abcd]	2.102[cde]	1.791[bcdef]	1.159[cd]	1.645[de]
9	1.350[abc]	1.055[cd]	0.918[cd]	1.436[e]	1.18[efg]	0.566[e]	1.084[fg]
10	1.195[bc]	1.179[bcd]	0.901[cd]	2.416[abcde]	1.133[efg]	0.892[de]	1.286[efg]
11	0.988[bc]	1.273[abcd]	0.451[d]	1.717[de]	1.036[fg]	0.588[e]	1.009[g]
12	1.101[bc]	1.411[abcd]	1.098[bcd]	2.796[abcd]	1.746[cdefg]	0.681[de]	1.472[def]

*Distinct letters above values within a column indicate significant (p<0.05) differences

Table 5.10: Mean Leaf Area Index (LAI) of 14 canola cultivars of South Africa, for the year 2020, at six field trials 90 days after first emergence (DAE). Cells with green and red shading indicate the highest (LAI>6.0) and lowest (LAI<3.0) performing values per column, respectively

Cultivar no.	Riversdale	Hopefield	Tygerhoek I	Tygerhoek II	Langgewens I	Langgewens II	Mean LAI
Conventional Cultivars							
6	3.380^{cd}	1.767^{c}	4.470^{abc}	4.013^{b}	1.674^{g}	2.798^{ab}	3.017^{e}
8	3.251^{d}	2.295^{bc}	3.337^{bc}	4.337^{b}	2.249^{defg}	1.754^{b}	2.871^{e}
13	5.831^{bc}	4.719^{ab}	4.506^{abc}	6.711^{ab}	2.904^{cde}	2.877^{ab}	4.591^{bc}
14	3.599^{cd}	0.861^{c}	4.284^{bc}	4.322^{b}	1.955^{fg}	2.271^{ab}	2.882^{e}
Clearfield (CL) Cultivars							
1	6.957^{ab}	2.874^{bc}	3.057^{c}	4.389^{b}	3.095^{cd}	2.508^{ab}	3.813^{cde}
2	8.604^{a}	3.491^{bc}	5.412^{ab}	7.385^{ab}	3.230^{c}	3.851^{a}	5.329^{ab}
3	4.555^{bcd}	6.794^{a}	6.509^{a}	9.177^{a}	5.972^{a}	3.305^{ab}	6.052^{a}
4	4.734^{bcd}	1.869^{bc}	3.223^{c}	7.052^{ab}	2.658^{cdef}	2.972^{ab}	3.751^{cde}
Triazine Tolerant (TT) Cultivars							
5	4.070^{cd}	1.357^{c}	4.602^{abc}	5.342^{b}	3.278^{c}	2.835^{ab}	3.581^{cde}
7	4.892^{bcd}	2.136^{bc}	2.919^{c}	5.279^{b}	1.855^{fg}	2.888^{ab}	3.328^{de}
9	5.255^{bcd}	1.200^{c}	2.923^{c}	7.408^{ab}	2.117^{efg}	2.186^{ab}	3.515^{cde}
10	3.857^{cd}	2.721^{bc}	3.410^{bc}	4.122^{b}	1.711^{g}	2.927^{ab}	3.125^{de}
11	3.397^{cd}	1.400^{c}	3.204^{c}	5.232^{b}	2.283^{defg}	2.405^{ab}	2.987^{e}
12	5.047^{bcd}	1.951^{bc}	3.864^{bc}	6.337^{ab}	5.013^{b}	3.143^{ab}	4.226^{bcd}

*Distinct letters above values within a column indicate significant ($p<0.05$) differences

5.3.5 Yield

Several statistical differences were recorded between the different canola cultivars tested with regards to their mean final yields at each trial site and the mean yield for all trial sites. Cultivars are represented in their three groups, representing their herbicide resistance traits, for each trial including a mean yield column (Table 5.11).

The yield results for each cultivar at each trial including a mean yield column is described below by dividing results into three categories i.e., high, medium and low performing categories. Cultivars from different categories do not necessarily differ significantly ($p<0.05$), which can be seen in Table 5.11. Yield categories are described as >3500 kg ha^{-1} (high), 3000 – 3500 kg ha^{-1} (medium) and <3000 kg ha^{-1} (low).

Mean yield results recorded at Riversdale were exceptional overall with all the cultivars being in the highest performance category except for Cultivar 9 which is the only cultivar categorised in the medium performance category. None of the cultivars were categorised within the low performance category. Interestingly, all the Clearfield cultivars and one conventional cultivar (Cultivar 13) achieved yields in the excess of 4 400 kg ha^{-1}. Two conventional cultivars (8 and 14) achieved yields of less than 4 000 kg ha^{-1}, very similar to the yields produced by the TT cultivars.

Hopefield recorded very different results when compared to Riversdale. All the mean cultivar yields were categorised within the low performance category except for Cultivars 6 and 13. Cultivars 6 and 13 recorded yields within the medium performance category with 3009 kg ha^{-1} and 3084 kg ha^{-1}, respectively. No cultivar recorded yields within the high-performance category. Only the TT Cultivars 7, 9, 11 and 12 had significantly lower yields than the two top performing cultivars at the Hopefield trial.

Tygerhoek I showed that Cultivars 2, 3, 4, 5 and 13 were the cultivars within the high performing category with regards to their mean yields. Cultivars 1, 6, 8, 10, 12 and 14 were categorised within the medium performance category with mean yields between 3000 and 3500 kg ha^{-1}. Cultivars 7, 9 and 11 recorded yields within the low performance category, keeping in mind that these are TT cultivars. They were however not significantly different from TT Cultivars 10 and 12 and conventional Cultivars 6, 8 and 14.

Tygerhoek II also showed excellent results with none of the cultivars being in the low performance category. Cultivars 1, 2, 3, 4, 6, 8, 10 and 13 were all within the high-performance category with Cultivars 5, 7, 9, 11, 12 and 14 recording medium performance. Cultivars 2, 4 and 13 produced more than 4000 kg ha^{-1}.

Yield results recorded at the Langgewens I trial showed Cultivars 1, 2, 3, 4, 6 and 13 to be within the highest performance category. Cultivars 7, 8, 9, 10 and 14 were categorised within the lowest performing category with yields below 3000 kg ha^{-1}. Therefore Cultivars 5, 11 and 12 were within the medium performance category although not necessarily significantly yielding more than the lowest category cultivars.

Langgewens II recorded Cultivars 1, 2, 4 and 6 as the cultivars with yields above 3500 kg ha^{-1}. Cultivars 3, 5, 7, 8, 10 and 14 were categorised as medium performing cultivars and Cultivars 9, 11, 12 and 14 as low performing cultivars. Cultivars 1, 2, 4 and 6 were however only significantly better than Cultivars 9, 11 and 14 with Cultivar 12 differing significantly from Cultivars 1, 2 and 4 but not Cultivar 6.

For the mean yield results across all the trials, Cultivars 1, 2, 3, 4, 6 and 13 were the cultivars with significantly ($p<0.05$) higher yields and were categorised in the high-performance category. Cultivars 5, 8 and 10 were within the medium performing category and Cultivars 7, 9, 11, 12 and 14 within the lowest performing category, keeping in mind that Cultivars 7, 9, 11 and 12 are TT cultivars. With regard to mean yields, the cultivars in the highest category had significantly higher yield results than all the other cultivars.

Since TT cultivars are expected to record lower yields when compared to Conventional and CL cultivars, the mean yield results for the TT cultivars are considered separately. The mean yields across all trials for the TT cultivars showed Cultivars 5 and 10 to be the best performing overall and Cultivars 7, 9, 11 and 12 recording the lowest yields. Cultivar 9 was the cultivar that showed the lowest performance across all trials and had the lowest final mean yield but did not differ significantly from TT Cultivars 7, 11 and 12.

5.3.6 Relationships of selected seed characteristics and plant growth parameters towards mean yield

All the pairwise coefficient of determination (R^2) values for 15 seed and plant quality parameters towards the final yield of tested cultivars are reported in Table 5.12 below. None of the general seed quality or seed vigour testing parameters had a significant effect ($R^2 > 5.0$) on mean yields of the field trials. Biomass (45 DAE), Biomass (90 DAE), LAI (14 DAE) and LAI (45 DAE) were the only parameters that had an effect on yield with R^2 values between 0.5 and 0.7, as seen in Table 5.12.

Table 5.11: Mean yield (kg ha^{-1}) of 14 canola cultivars of South Africa, for the year 2020, at six field trials. Cells with green and red shading indicate the highest (>3500 kg ha^{-1}) and lowest (<3000 kg ha^{-1}) performing values per column, respectively

Cultivar no.	Riversdale	Hopefield	Tygerhoek I	Tygerhoek II	Langgewens I	Langgewens II	Mean Yield
Conventional Cultivars				*(kg ha^{-1})*			
6	4202^{bcd}	3009^{ab}	3427^{cdef}	3891^{abcde}	3579^{ab}	3513^{abc}	3604^{a}
8	3819^{def}	2343^{abcd}	3111^{defgh}	3575^{def}	2826^{d}	3430^{abcd}	3171^{bc}
13	4649^{ab}	3084^{a}	3613^{bcd}	4291^{ab}	3668^{a}	3203^{abcde}	3751^{a}
14	3729^{def}	2035^{bcde}	3030^{efgh}	3316^{ef}	2712^{d}	2874^{e}	2949^{cd}
Clearfield (CL) Cultivars							
1	4626^{ab}	2650^{abc}	3489^{cde}	3595^{cdef}	3934^{a}	3570^{a}	3644^{a}
2	4414^{abc}	2681^{ab}	3754^{abc}	4181^{abc}	4072^{a}	3550^{ab}	3775^{a}
3	4459^{ab}	2777^{ab}	4159^{a}	3955^{abcd}	3773^{a}	3335^{abcde}	3743^{a}
4	4710^{a}	2111^{bcde}	4062^{ab}	4396^{a}	3756^{a}	3513^{ab}	3758^{a}
Triazine Tolerant (TT) Cultivars							
5	3957^{cde}	2078^{bcde}	3541^{bcde}	3496^{def}	3497^{abc}	3015^{bcde}	3264^{b}
7	3718^{ef}	1487^{e}	2857^{gh}	3112^{f}	2956^{cd}	3327^{abcde}	2910^{cd}
9	3409^{f}	1686^{de}	2588^{h}	3149^{f}	2789^{d}	2938^{de}	2760^{d}
10	3514^{ef}	2366^{abcd}	3043^{efgh}	3675^{bcdef}	2832^{d}	3129^{abcde}	3093^{bc}
11	3592^{ef}	1826^{cde}	2927^{fgh}	3263^{f}	3069^{bcd}	2928^{de}	2934^{cd}
12	3838^{def}	1634^{de}	3135^{defg}	3217^{f}	3079^{bcd}	2977^{cde}	2980^{cd}

*Distinct letters above values within a column indicate significant (p<0.05) difference.

Table 5.12: Coefficient of determination (R^2) values for each pairwise interaction combination towards the final yield results of certain general seed quality, seed vigour and plant quality parameters used for assessing 14 canola cultivars of South Africa for the year 2020. Cells with red shading indicate all R^2 values between 0.5 – 0.7 (moderate effect) and green shading values above 0.7 (strong effect) towards yield

Seed Quality Parameters	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	**16**
1	**1**	0.685	0.925	0.853	0.715	0.851	0.659	0.520	0.483	0.323	0.000	0.096	0.413	0.197	0.028	**0.026**
2	0.685	**1**	0.732	0.782	0.660	0.803	0.586	0.655	0.743	0.227	0.178	0.142	0.304	0.148	0.087	**0.000**
3	0.925	0.732	**1**	0.834	0.705	0.863	0.708	0.540	0.566	0.236	0.155	0.108	0.321	0.133	0.058	**0.008**
4	0.853	0.782	0.834	**1**	0.646	0.771	0.562	0.653	0.668	0.360	0.264	0.178	0.467	0.254	0.111	**0.031**
5	0.715	0.660	0.705	0.646	**1**	0.761	0.817	0.510	0.596	0.295	0.193	0.148	0.316	0.149	0.051	**0.027**
6	0.851	0.803	0.863	0.771	0.761	**1**	0.855	0.571	0.630	0.283	0.196	0.143	0.359	0.166	0.034	**0.020**
7	0.659	0.586	0.708	0.562	0.817	0.855	**1**	0.512	0.594	0.277	0.204	0.193	0.311	0.146	0.027	**0.041**
8	0.520	0.655	0.540	0.653	0.510	0.571	0.512	**1**	0.868	0.356	0.440	0.323	0.517	0.341	0.291	**0.141**
9	0.483	0.743	0.566	0.668	0.596	0.630	0.594	0.868	**1**	0.403	0.446	0.440	0.517	0.363	0.379	**0.127**
10	0.323	0.227	0.236	0.360	0.295	0.283	0.277	0.356	0.403	**1**	0.856	0.706	0.933	0.902	0.303	**0.499**
11	0.000	0.178	0.155	0.264	0.193	0.196	0.204	0.440	0.446	0.856	**1**	0.790	0.919	0.966	0.360	**0.699**
12	0.096	0.142	0.108	0.178	0.148	0.143	0.193	0.323	0.440	0.706	0.790	**1**	0.782	0.782	0.561	**0.677**
13	0.413	0.304	0.321	0.467	0.316	0.359	0.311	0.517	0.517	0.933	0.919	0.680	**1**	0.931	0.306	**0.525**
14	0.197	0.148	0.133	0.254	0.149	0.166	0.146	0.341	0.363	0.902	0.966	0.782	0.931	**1**	0.352	**0.677**
15	0.028	0.087	0.058	0.111	0.051	0.034	0.027	0.291	0.379	0.303	0.360	0.561	0.306	0.352	**1**	**0.371**
16	**0.026**	**0.000**	**0.008**	**0.031**	**0.027**	**0.020**	**0.041**	**0.141**	**0.127**	**0.499**	**0.699**	**0.677**	**0.525**	**0.677**	**0.371**	**1**

*1 - Germination Percentage
2 - Glasshouse Emergence Percentage
3 - AA Germination (24hours)
4 - AA Emergence (24hours)
5 - Planting Depth (10mm)
6 - Planting Depth (20mm)
7 - Drought Stress
8 - Field Emergence (14DAE)
9 - Field Establishment (45DAE)
10 - Biomass (14 DAE)
11 - Biomass (45 DAE)
12 - Biomass (90 DAE)
13 - LAI (14 DAE)
14 - LAI (45 DAE)
15 - LAI (90 DAE)
16 - Yield

5.4 Discussion

5.4.1 Plant population

According to McDonald and Copeland (1997) crop seed is the reproductive units of plants, and should be able to germinate and establish normal seedlings to develop into a productive plant. Uniform seed emergence and crop establishment is therefore one of the most important factors in crop production systems and has a determining effect on the total yield (Yang et al. 2014; Finch-Savage and Bassel 2015). Field emergence should thus be as uniform and abundant as possible to ensure ample plants and produce an optimal yield.

Optimal canola plant populations in South Africa are considered to be between 40 to 60 plants per square meter as an average for all varieties (DeVilliers and Agenbag 2007; French and Seymour 2017). Harker et al. (2012) and the Protein Research Foundation (2018) reported that in fact only 50-70% of planted canola seeds will eventually emerge and establish into a productive plant.

When considering each trial site separately certain general results can be explained by some external factors affecting emergence. Riversdale for instance recorded good establishment results, which was expected since sufficient rainfall and moisture was present during planting, emergence and establishment.

The Hopefield trial was planted in dry conditions with only 1.22% moisture in the top 150 mm of the sandy soil profile and the first sufficient rainfall event (16 mm) only occurring on the 10th of June, 22 days after planting. These dry conditions can possibly explain the somewhat lower emergence counts at 14 DAE and the better results at 45 DAE as also explained by Gusta et al. (2003), since frequent rainfall was received after the 10th of June.

Tygerhoek I showed a large decrease in plant populations between 14 and 45 DAE indicating a satisfactory start but a low final establishment. Data collection at 14 DAE showed differences in plant sizes within each plot and was most probably caused by the fact that planting took place in a moist soil (10.1%) and was followed only by small rainfall events (<1 mm) that made shallower seeds emerge first and the rest after the first substantial rainfall event (9.7 mm) on 28 June, 21 days after planting. The uneven emergence was possibly the cause for the low establishment populations at 45 DAE since larger plants would have killed off the smaller plants by means of competition for water and nutrients and even by means of an overshadowing effect, as also seen by McDonald et al. (2020). Rainfall data recorded at Riviersonderend during emergence and establishment of the Tygerhoek II trial showed that moisture was sufficient and this was confirmed by the high emergence and establishment performance overall.

Low emergence and establishment results for Langgewens I can be explained by the dry conditions during planting and emergence as also seen by Gusta et al. (2003). Soil moisture content during planting was only 2.98% in the top 150 mm and the first substantial rainfall event (21.8 mm) was only on the 25th of May, 14 days after planting. After the 21.8 mm rainfall event on the 25th of May the following significant rainfall was only received 15 days later on the 10th of June, thereby placing young seedlings under severe stress and that could have resulted in poor establishment percentages (Rezayian et al. 2018).

The Langgewens II trial was planted into moist soil, with 9% soil moisture in the top 150 mm. The first substantial rainfall event after planting only took place 8 days after planting into the moist soil and the temperature for this period also being higher than the long-term average. The lower emergence performance at 14 DAE of certain cultivars for this trial is possibly as a result of secondary dormancy of some seeds because of moisture that was available during planting to make the seed swell and then followed by a dry spell with high temperatures (Momoh et al. 2002). The secondary dormancy resulted in an uneven emergence and therefore explains the low establishment results at 45 DAE with smaller plants dying off because of competition for water and nutrients as well as an overshadowing effect from larger plants.

Overall difference in plant populations between 14 DAE and 45 DAE evaluations is due to seedlings that have died off and which can be due to several reasons and is normal during establishment (Nakashizuka 1988). Thus the 45 DAE plant population is the better indication of overall crop establishment. Populations at 14 DAE can be seen as emergence results and populations at 45 DAE as establishment results.

Cultivars 2, 5, 6, 7, 11, 12 and 13 all recorded overall mean field establishment (45 DAE) percentages of above 50% across all trials which is considered normal for canola (Harker et al. 2012; PRF 2018). The cultivars that showed the best field establishment over all the trails, at 45 DAE, were Cultivars 5, 6 and 13 with mean emergence percentages of 58.6%, 57.9% and 59.8% of planted seeds, respectively. These results do not correspond entirely with seed quality and vigour results in previous chapters.

The lowest performing cultivars after 45 DAE were Cultivars 1, 4, 8, 9, 10 and 14 which all recorded mean field establishment values, across all trials, below 50% of planted seeds. Cultivars 1, 4 and 9 only recorded establishment results below 50% for the 45 DAE evaluation and not the 14 DAE evaluation which could be caused by several reasons as described by Nakashizuka (1988). Cultivars 8 and 14 were the lowest ranking cultivars and recorded the lowest overall mean emergence throughout all field trials for both evaluations. The general seed quality (Chapter 3) and seed vigour (Chapter 4) results also recorded Cultivars 8 and 14 as the lowest performing cultivars and correlates with the actual field emergence and establishment results.

Overall, these establishment results do not correspond too well with predicted emergence potential results from previous chapters (Chapters 3 and 4) but do still correlate to a certain extent. Cultivars 5, 6 and 13 did not necessarily always perform the best in general seed quality and seed vigour testing but were always among the top performing cultivars. Cultivars 7 and 12, on the other hand, which performed the best in general seed quality and seed vigour testing did not perform the best with regards to field emergence and establishment but were still among the top performing cultivars with regards to establishment. This slight variation between top performing cultivars can most possibly be explained by natural variation due to the random nature of the trials and it is believed that all top performing cultivars will deliver satisfactory results with regards to establishment and yield.

5.4.2 Relationships between seed quality and vigour parameters towards mean plant populations

Results from the multiple pairwise regression table (Table 5.4) compared all the general seed quality and seed vigour testing parameters, tested in previous chapters, to determine the relationship of each parameter towards the plant population results for both the 14 DAE and 45 DAE evaluations. According to Moore et al. (2013) coefficient of determination (R^2) values can be categorised as weak ($R^2 < 0.5$), moderate ($0.5 < R^2 < 0.7$) and strong ($R^2 > 0.7$) effects.

Table 5.4 reports all the coefficient of determination (R^2) values for each interaction combination of all the tested parameters. The parameters that had a moderate effect ($0.5 < R^2 < 0.7$), according to Moore et al. (2013), on the plant populations at 14 DAE was germination percentage, glasshouse emergence, AA germination (24 hours), AA emergence (24 hours) planting depth (10 mm), planting depth (20 mm) and the drought stress test (Table 5.4). The 45 DAE plant population parameter recorded an R^2 value higher than 0.7 towards the 14 DAE plant populations, indicating a strong relationship but cannot be used to predict field emergence.

With regards to the 45 DAE plant populations parameter, glasshouse emergence, AA germination (24 hours), AA emergence (24 hours) planting depth (10 mm), planting depth (20 mm) and the drought stress parameters all recorded R^2 values between 0.5 - 0.7, indicating moderate relationships (Moore et al. 2013). The 14 DAE plant population parameter recorded an R^2 value higher than 0.7 compared to plant populations at 45 DAE, indicating a strong relationship, but again cannot be used to predict field emergence since 14 DAE plant population is in fact the field emergence results.

Mean glasshouse emergence had the best relationship with plant populations at 45 DAE, with regards to R^2. The R^2 value, of 0.743, shows a strong effect ($R^2 > 0.7$) according to Moore et al. (2013). Therefore, the mean glasshouse emergence is in fact the best testing parameter to estimate field establishment in this study and the other moderate parameters will also give good indications.

Overall, for this study, general seed quality parameters do not give a good indication of field emergence and establishment, except for germination percentage that has a moderate relationship towards field emergence but not establishment. These results also corresponds to results published by Buckley and Irvine (2009) and confirms the statement made by Hampton (1993) suggesting that vigour testing provides a more sensitive index of seed quality compared to germination percentage.

5.4.3 Biomass

Canola biomass production during the first 30 days after first emergence (DAE) is relatively slow as the plants and their leaves are still small which means their photosynthetic capabilities are limited (Malhi et al*.* 2007). A rapid increase in growth occurs from early to late bud formation (approximately 42 – 49 DAE) and maximum biomass is reached at the pod formation stage (approximately 74 – 84 DAE) (Malhi et al*.* 2007). After maximum biomass has been reached biomass decreases rapidly as plants shed their leaves. Since different cultivars have different genetic growth patterns, cultivars could possibly be in different stages of growth when data collection was done.

Cultivar 2 was the highest performing cultivar at the 14 DAE evaluation, indicating high seed vigour of this cultivar (Finch-Savage and Bassel 2015). Cultivar 2 had the highest mean biomass across all trials and all evaluations, except at 90 DAE. The change in performance at the 90 DAE biomass results can be described by different cultivars finding themselves in different development stages as a result of genetic growth patterns (Malhi et al*.* 2007). Cultivar 2 is a Clearfield cultivar and was therefore expected to have a high biomass, especially compared to the TT cultivars.

Since Triazine Tolerant (TT) cultivars are expected to report lower biomass values than the Conventional and CL cultivars as they have lower yield potentials and therefore grow into a smaller plant with lower biomass, we can compare them separately (Robertson et al. 2002).

Cultivars 5 and 7 were the two highest performing cultivars overall of the TT cultivars, with regards to mean biomass, across all trials and all the evaluations. Cultivar 5 was not one of the highest performing cultivars at 14 DAE but indeed so at 45 and 90 DAE. Cultivar 12 was not categorised as one of the highest performing TT cultivars across all trials and at all evaluations but was in fact one of the highest performing cultivars at 14 DAE. This initial high growth rate of Cultivars 7 and 12 is considered to be because of high seed vigour and correlates with seed vigour testing results from Chapter 4 (Finch-Savage and Bassel 2015).

Over all the trials for all the evaluations, Cultivars 8 and 14 were generally the lowest performing cultivars with regards to mean biomass. These two cultivars are both grouped under Conventional cultivars and recorded unexpected low biomass values and are therefore believed to have had low seed vigour. This also correlates well with the seed vigour testing results from Chapter 4 (Robertson et al*.* 2002; Finch-Savage and Bassel 2015).

5.4.4 Leaf area index (LAI)

Canola leaf area generally follows the same growth and development pattern as for biomass and can vary between cultivars as a result of different genetic growth patterns. As mentioned above in section 5.4.3. leaves are still small and develop at a slow rate before 30 DAE (Malhi et al*.* 2007). Maximum leaf development, amount of leaves and LAI is usually noted at the flowering stage of canola development, whereafter leaves start to drop off and LAI decreases (Khayat et al*.* 2018).

Cultivars 1, 2, 6 and 13 were the highest performing cultivars at the 14 DAE and 45 DAE evaluations with regards to mean LAI. Cultivar 3 was the cultivar with the highest LAI at 90 DAE. The change in highest ranking cultivars at 90 DAE can be described by different cultivars finding themselves in different development stages as a result of genetic growth patterns (Malhi et al*.* 2007). All these cultivars are still considered high performing cultivars and these results correlate well with seed quality and vigour results from Chapters 3 and 4.

Cultivars 8 and 14 recorded the lowest mean LAI over all evaluations, indicating low photosynthetic potentials throughout the season (Fang and Liang 2008). Cultivar 11 also showed to be one of the lowest performing cultivars with regards to LAI at 90 DAE. Cultivar 11 is a TT cultivar which is expected to be lower than Conventional and Clearfield cultivars. This is why the TT cultivars are separately described below and could also possibly have found themselves in a lower performance category because of lower growth potential (Robertson et al. 2002; Malhi et al. 2007).

When comparing the TT cultivars with one another, Cultivars 7 and 12 had the highest mean LAI over all the evaluation times, although not always significantly. Cultivar 11 recorded the lowest mean LAI at 14 DAE, 45 DAE and 90 DAE.

With regards to results from Chapter 3 the seed with the highest general quality correlating with LAI results were Cultivars 7 and 12 (best performers in Chapter 3) and were also the two best performing TT cultivars with regards to LAI. Seed vigour results from Chapter 4 also correlated well with LAI results.

5.4.5 Yield

The 2020 canola production season in the Western Cape was mostly ideal and this was confirmed by exceptional yields throughout. The average canola yield in the production areas of the Western Cape for dryland production generally varies between 1800 – 2500 kg ha^{-1} (Thomas 2012).

Exceptionally good yields overall for all the tested cultivars were recorded at Riversdale and Tygerhoek II, with none of the cultivars recording mean yields below 3000 kg ha^{-1}. The excellent yields from these two trials can be explained by the good establishment of the canola and good rainfall during the season. Low temperatures during flowering, in August and September, where also conducive to high yields (Angadi et al. 2003; PRF 2018).

Mean yield results at Tygerhoek I, Langgewens I and Langgewens II also showed high yields with none of the mean yields below 2500 kg ha^{-1}. The high yields at these trials can also be explained by the good canola production conditions during the 2020 production season. Triazine Tolerant (TT) cultivars have lower yield potentials compared to Conventional and CL cultivars and this can be seen at these three trials, as shown in Table 5.11 (Robertson et al. 2002). The TT cultivar, Cultivar 5 showed impressive results at all three trials, especially at Tygerhoek I. The most concerning results in terms of yield from these three trials is the low yields of Cultivars 8 and 14, compared to the other conventional and all the CL cultivars.

The mean yield results from the Hopefield trial indicated overall low performance by all the cultivars, compared to the other trials. The Hopefield trial site is characterised by the sandy nature of the soil which already indicates a lower yield potential (GRDC 2018b). This trial also received lower than average rainfall during the flowering and pod filling stages in September and October, which will also have a negative effect on mean yield (Hbahar and Bahrani 2009). Although all the tested cultivars recorded lower yields overall when compared to other trials, Cultivars 6 and 13 were the two highest performing cultivars with mean yields of 3009 kg ha^{-1} and 3084 kg ha^{-1}, respectively.

For the mean yield results across all the trials, Cultivars 1, 2, 3, 4, 6 and 13 were the cultivars with significantly higher mean yields. Cultivars 5, 8 and 9 were within the medium performing category and Cultivars 7, 9, 11, 12 and 14 within the lowest performing category, keeping in mind that Cultivars 7, 9, 11 and 12 are TT cultivars. Cultivar 14 is the most concerning cultivar since it a conventional cultivar and was placed in the lowest performance category for this study. Cultivar 8 compensated well despite a low establishment and overall performance. In a growing season with less optimal conditions than 2020 it is believed that the cultivars would not have compensated as much (GRDC 2018a).

As TT cultivars are expected to deliver lower yields compared to conventional and CL cultivars, the mean yield results for the TT cultivars were inspected separately as well. The mean yields across all trials for the TT cultivars showed Cultivars 5 and 10 to be the best performing overall, while Cultivars 7, 9, 11 and 12 recorded the lowest performance. Cultivar 9 was the cultivar that showed the lowest performance across all trials and had the lowest final mean yield.

5.4.6 Relationships of selected seed characteristics and plant growth parameters towards mean yield

None of the general seed quality or seed vigour testing parameters showed a significant effect (R^2 > 5.0) on the mean yields of the field trials (Moore et al. 2013). Biomass (45 DAE), Biomass (90 DAE), LAI (14 DAE) and LAI (45 DAE) were the only parameters that had a significant effect on yield, as also stated by Zhang and Flottmann (2016), with R^2 values between 0.5 and 0.7 but that cannot be used to predict field performance before planting.

The 2020 production season in the Western Cape of South Africa was a very good one with regards to climatic conditions and produced exceptional yields throughout. Since the canola crop is able to compensate for poor establishment and still produce a good yield, certain cultivars had the opportunity to compensate (Angadi et al. 2003; GRDC 2018a). Therefore, it is believed that in this study the effects of general seed quality and seed vigour testing parameters towards the yield were overshadowed by the good growing conditions of 2020, similar to certain results reported by Elliott et al. (2007). Although seeding densities were not covered in this study, the effect of lower quality seed towards yield might have been intensified by lower planting densities, as commonly planted by producers.

To further investigate the relationship between general seed quality and seed vigour on final yield, the predicted best and worst performing cultivars from parameter testing in Chapter 3 and 4 can be compared to the final yield results.

In Chapter 3, Cultivars 7, 10 and 12 were the cultivars that performed best in general seed quality testing. All three cultivars are TT cultivars and can therefore only be compared to the other TT cultivars tested with regards to yield. The field performance prediction did not have a strong relationship with mean yield results with Cultivars 7 and 12 actually among the cultivars with the lowest yields. Cultivar 10 showed a higher mean yield compared with other TT cultivars.

In Chapter 4, Cultivars 6, 7, 12 and 13 were the cultivars which showed the highest seed vigour and therefore the highest field performance potential according to seed vigour predictions. Although Cultivars 6 and 13 recorded some of the highest mean yields, Cultivars 7 and 12 on the other hand recorded some of the lowest mean yields.

Cultivars 8 and 14 showed the lowest field performance potential in Chapter 3 and 4. These two cultivars were under the lowest performing cultivars throughout this chapter, with regards to plant population, biomass and LAI. These two cultivars are both conventional cultivars and should therefore only be compared to the other conventional and CL cultivars, since TT cultivars genetically produce a lower yield. Compared to the other conventional and all CL cultivars these two cultivars recorded the lowest mean yields. The mean yields of these cultivars were similar to the yields of the TT cultivars.

5.5 Conclusions

The 2020 production season in the Western Cape of South Africa was a very good season with regards to climatic conditions. Since the canola crop is able to compensate for poor establishment and still produce a good yield, certain cultivars had the opportunity to compensate (Angadi et al. 2003; GRDC 2018a). Therefore, it is believed that in this study the effects of general seed quality and seed vigour testing parameters on yield were less clear because of the good growing conditions of 2020 and the ability of canola to compensate, although it is known that genetics plays a major role in the yield potential of each cultivar.

Even though the growing conditions were very good and crops had ample opportunity to compensate for low establishment, throughout this study it was clear that Cultivars 8 and 14 were the lowest performing cultivars. These cultivars had the lowest general seed quality (Chapter 3) and seed vigour (Chapter 4), which correlated with the field trial results where these two cultivars were always the lowest performing cultivars.

From the general seed quality parameters, only germination percentage showed a moderate correlation with seed emergence but not establishment. All the seed vigour parameters tested, on the other hand, showed moderate relationships with field emergence and establishment. None of the general seed quality or seed vigour testing parameters had a significant effect ($R^2 > 5.0$) on yield, biomass or LAI of the field trials.

To conclude this chapter, it was observed that seed vigour parameters are best to predict field emergence and establishment. Although seed vigour gives a good indication of field establishment, there is no statistical correlation towards biomass, LAI and eventually yield.

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Chapter 6

General conclusion and future research

6.1 General conclusion

The establishment of any crop is one of the most important parts of a successful production year, with several factors that can influence the establishment (Nakashizuka 1988; Finch-Savage and Bassel 2015). Ensuring the uniform emergence of seedlings thus enabling a uniform stand and ultimately uniform ripening, with minimum seed losses during harvest, contribute to an optimal yield (Hampton and Tekrony 1995; Yang et al. 2014). To safeguard the best possible establishment, most producers make use of high-quality certified seed to establish their crops. Certified seed companies generally make use of germination percentage as seed quality indicator which is probably the most common in the world (Hampton 2002). Germination tests usually fail to take into account the ongoing seed deterioration process, physical seed damage and quality factors which can be reflected by seed vigour testing (McDonald and Copeland 1997; Elias and Copeland 2001).

This study was therefore initiated with the main aim to compare the effectiveness of general seed quality results, such as germination percentage (seed viability), thousand seed mass and seed size as well as certain seed vigour results, to the actual field establishment success. The aim of the study was investigated by means of three main objectives.

The first objective was to determine several general seed quality parameters of South African canola cultivars and compare them to glasshouse emergence results. This was done to determine which general seed quality parameter best correlates to glasshouse emergence and to try and estimate potential field emergence and establishment. From the results within this chapter, it could be concluded that that mean germination percentage is the general seed quality parameter that correlates best with seed glasshouse emergence. Germination percentage is therefore the best general seed quality parameter for the indication of seed emergence potential, although it only gave a moderate indication. Cultivars 7, 10 and 12 showed the best overall general seed quality, whereas Cultivars 8 and 14, showed to be the lowest. These findings were confirmed by the glasshouse emergence results.

The second objective was to determine separations between South African canola cultivars with regards to seed vigour to try and estimate potential field emergence and establishment. After making use of several seed vigour testing methods, namely germination and emergence after accelerated ageing (AA), planting depth emergence and drought stress emergence, certain performance differences between cultivars were clear. Cultivars 6, 7, 12 and 13 showed the highest overall seed vigour compared to the other cultivars tested in this study. The cultivars with the lowest seed vigour and estimated field emergence and establishment potential were Cultivars 8 and 14.

The third and final objective was to gather field trial data from several canola cultivar trials across the Western Cape of South Africa and correlate actual field performance results to general seed quality and seed vigour results. The cultivars that recorded the lowest field emergence (after 14 DAE) and establishment (after 45 DAE) were identified as Cultivars 8, 10 and 14. Cultivars 8 and 14 was predicted, from seed quality and vigour results, to have the lowest overall field performance. Cultivar 10 on the other hand was not expected to have such a low emergence and field performance. The results from the pairwise coefficient of determination (R^2) values towards the field emergence and establishment indicated that germination percentage only had a moderate relationship to field emergence (14 DAE) and no relationship to overall establishment (45 DAE). When considering seed vigour parameters, AA germination (24 hours), AA emergence (24 hours), planting depth (both 10 mm and 20 mm) and the drought stress emergence parameters all indicated a moderate relationship to field emergence and establishment. General glasshouse emergence results at a planting depth of 15 mm showed the best correlation with field establishment (45 DAE) by means of a strong pairwise interaction (R^2 > 0.7). Although certain general seed quality and seed vigour testing parameters showed a significant effect (R^2 > 5.0) to emergence and establishment, a weak relationship was obtained to biomass production, LAI and final yield of the field trials.

After analysis of several general seed quality, seed vigour and field trial results during this study it could be concluded that seed vigour parameters are best to predict potential field emergence and establishment. Although seed vigour gives a good indication of field establishment, there is no significant statistical correlation towards biomass, LAI and eventually yield.

6.2 Limitations of the study

In this study a large number of research sites over an extensive area was covered and made it very difficult to do data collections according to crop growth stages rather than days after first emergence. Data collection according to growth stage rather than days after first emergence could possibly have exposed even more valuable information, especially in the later stages of the trials. The large distances between research sites also made it difficult at times to do regular inspections and crop management sprays, especially with regards to herbicides with two plots lost at the Hopefield trial because of weed infestation.

Biomass data collection and calculation was done by converting results from a number of plants per plot to the mean biomass per hectare by using the mean plant populations. The biomass should rather be determined by means of sampling a certain area and converting that value to a biomass per hectare result, since it is believed to be more accurate.

During germination testing it was also noted that petri dishes should be placed inside a plastic bag to prevent the rapid drying of dishes.

Although it is known that cultivar genetics plays a major role in the eventual yield, the 2020 production season in the Western Cape of South Africa was a very good season with regards to climatic conditions and produced exceptional yields throughout. Since the canola crop is able to compensate for poor establishment and still produce a good yield, certain cultivars had the opportunity to compensate and it is believed that in this study the effects of general seed quality and seed vigour testing parameters towards the yield were slightly overshadowed by the good growing conditions of 2020.

6.3 Future research

Since it is clear that seed vigour testing gives a more sensitive index of seed quality compared to germination percentage and correlates better with field establishment potential, it is recommended that further studies be done to find the most effective and efficient vigour testing method. Efficiency of testing is crucial for seed companies and therefore an efficient and reliable test should be determined.

Future trials can also incorporate seeding densities within the study since producers generally establish canola at lower densities, which could intensify the effect of low performing seeds. Comparing seed of varying ages of the same cultivars in terms of general seed quality and seed vigour parameters can also record interesting results on the ageing and deterioration of seed. Furthermore, farm retained seed can also be incorporated in future studies to indicate the possible impact of using retained seeds from hybrid canola cultivars, as at times is done in South Africa.

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